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THE ZUNI SALT LAKE[1]

N. H. DARTON
U. S. Geological Survey

Forty-two miles south-by-east from the Pueblo of Zuñi there is a small salt lake, affording a local supply of salt for the Indians and others. It occupies a portion of the bottom of a remarkable steep-sided, circular depression about a mile in diameter, near the center of which rise two fresh volcanic cinder cones. The depression appears not to be a volcanic crater, but has walls of Cretaceous sandstone capped by a lava sheet and deposits of volcanic ejecta. One of the cinder cones rising near the center of the depression has a deep crater containing a pool of salt water at the lake-level.

This salt lake has been known to the Zuñi Indians for a very long period, and for a half-century or more to Mexicans and a few travelers. The first account of its geologic relations was a brief note by E. E. Howell, of the Wheeler Survey,[2] who visited the locality in 1873. This observer noted the sandstone walls capped in part by lava flows, and the cinder cone with deep crater, but offered no suggestion as to their origin. Professor C. L. Herrick visited the salt lake in December, 1899, and afforded some further descriptive details.[3]

[1] Read to the Geological Society of America, December 28, 1904, and published by permission of the director of the U. S. Geological Survey.

[2] George M. Wheeler, "U. S. Geographical Surveys West of 100th Meridian," *Reports*, Vol. III, pp. 538, 539.

[3] *American Geologist*, Vol. XXV.

He suggested that the depression might be due to the solution of the salt in underlying strata, causing the depressed area to subside.

The lake is shallow, and its waters are saturated with common salt, containing 26 per cent. in December, 1899, according to Professor C. L. Herrick. As the natural evaporation progresses, salt

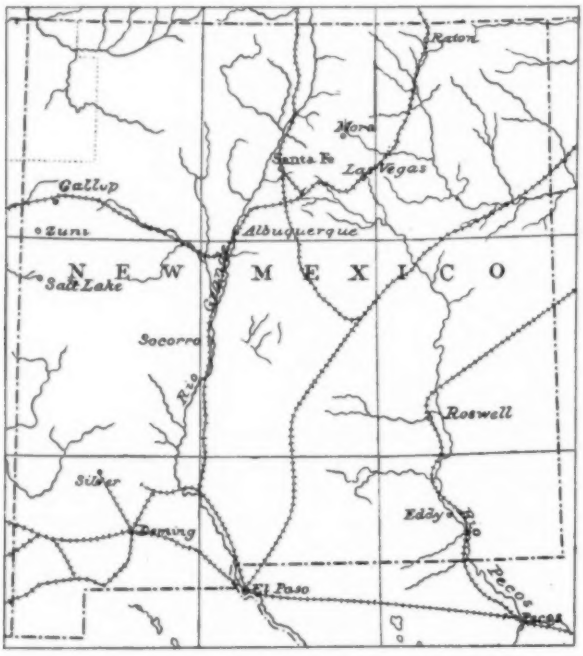

FIG. 1.—Map of New Mexico, showing the location of the salt lake south of Zuñi.

is constantly deposited, and doubtless a large amount has accumulated. On the north shore of the lake there is a small settlement of Mexicans, who gather the salt for shipment, and many persons make special trips to the lake, often from long distances, to collect a load of the salt. The quality is excellent and the supply large. Only the crudest methods are employed for gathering the freshly deposited salt in the shallow waters near the north shore of the lake.

The Indians have utilized this source of salt for many centuries and regard the lake with great veneration.

There is a large amount of salt in the lake and springs. An average of about three tons a day is produced by very crude methods; it is valued at from $2 to $2.50 a ton. This industry sustains the small settlement of Mexicans.

The origin of the salt is believed to be in springs which rise under the water near the south end of the lake. If the water from these is not saturated with salt, the percentage increases by the great evaporation in this arid region. Undoubtedly it is derived from the underlying Red Beds, which have the relations shown in the cross-sections. These Red Beds outcrop at no great distance, and yield salt springs at some points. A small amount of fresh water flows into the lake, partly from a small spring on the east shore, which flows constantly, and partly from scanty rains falling directly into the depression, or running into it from a small drainage area lying mainly on the high slopes south. Although no deep borings have been made, the depression appears to contain a salt deposit of considerable thickness, mixed with small amounts of mud washed from the surrounding slopes, and dust carried by the wind. Apparently the lake occupied the entire floor of the depression at one time, but, by evaporation and the deposition of mud, it has greatly diminished in size; doubtless the lake has been crowded over to the north side of the depression because the greater amount of detritus is deposited on the south side.

In the map and cross-sections of Fig. 2 are shown the principal features of the salt lake depression, and the photographs reproduced in Figs. 3–5 show the lake from three points of view.

The depression is in a plain sloping gently northward on the south side of the Carrizo Valley. A short distance to the south rises a line of cliffs of Cretaceous sandstones, in part capped by lava, while there is a corresponding ridge several miles north on the opposite side of the valley. The floor of the valley is Cretaceous sandstone, overlain in places by lava flows, one of which forms part of the upper wall of the northern, eastern, and southeastern sides of the depression. All about the margin of the depression there is a widespread mantle of fragmental material, mostly volcanic, which thickens toward

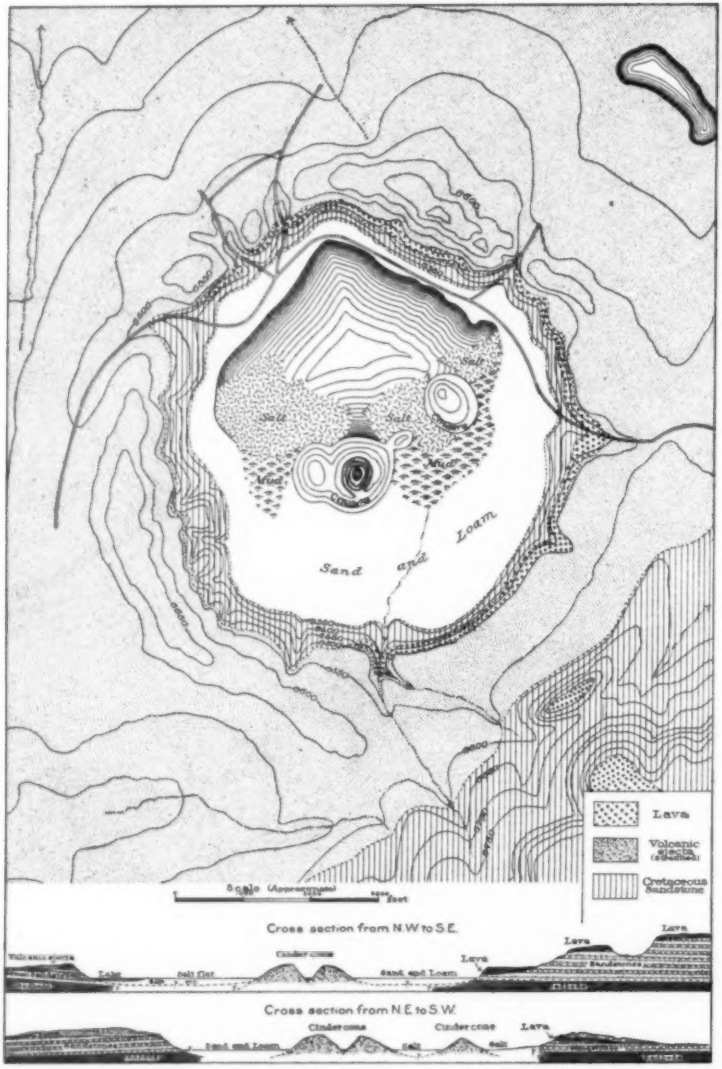

FIG. 2.—Sketch map and sections of Zuñi salt lake, New Mexico, by N. H. Darton. Contour interval 50 feet.

the rim. It attains a thickness of over 100 feet on the north and southwest portions of the rim, where it rises in a ridge of considerable prominence. The material is mostly stratified, fine-grained, and in part cross-bedded. It consists mainly of scoria, but includes fragments of various kinds of sedimentary rocks, including Carboniferous (Aubrey) limestones with characteristic fossils.[1]

The view from the rim of the depression is impressive. The ground sinks for 150 feet or more in a circular area a mile in diameter, with flat bottom in part occupied by the lake and in part by the glistening salt and mud flats. The two volcanic cones in the center of the basin are prominent features, rising steeply to an elevation of nearly 150 feet above the lake. The larger cone has a deep crater in its summit, which contains a circular pool, about 150 feet in diameter, at the lake level. The water of this pool is very salt, but several per cent. less so than that in the main lake. The cone is nearly circular, except on its western side, where it merges into the remains of a slightly older volcanic mass. The second cone is a short distance northeast, rising steeply out of the mud flat at the southeastern margin of the lake. It has no crater, is smaller, and appears to be somewhat older than the other cone. Both cones consist of scoria and other volcanic ejecta, and they are similar to the cones in the numerous lava fields of New Mexico. Walls of Cretaceous sandstone encircle the depression, which to the north, east, and southeast are capped by a sheet of lava from 30 to 50 feet thick. To the west and southwest the sandstone wall rises in cliffs and rocky slopes about 150 feet above the bottom of the depression, and is capped by rolling hills composed of beds of fragmental volcanic materials, while to the north, east, and south it rises from 60 to 70 feet to the base of the lava sheet. The lava sheet which caps the sandstone walls on the southeast, north, and east sides of the depression is an ordinary sheet of "malpais" or black lava, which appears to be older than the cinder cone with the crater in it.

[1] These fossils were determined by Dr. George H. Girty as follows:

Lophophyllum sp.	Phillipsia sp.
Productus ivesi.	Chonetes n. sp.
Productus mexicanus ?	Productus occidentalis.
Productus sp.	Seminula mexicana.
Bakewellia ? sp.	Schizodus sp.
Laeviadentalium cana.	Euomphalus sp.

FIG. 3.—Looking north across Zuñi salt lake, showing large cinder cone with crater. Ridge of scoria in middle-ground, sandstone plateau in distance.

The origin and history of the depression are an interesting problem. From the continuity of its sandstone walls, it clearly is not a portion of an old valley dammed by a lava stream, and it presents none of the ordinary features of a crater. In some respects it is comparable to "Coon Butte," a great depression west of Winslow in eastern Arizona, which, Mr. Gilbert has shown, is due to explosion, but although there is a ring of ejected rocks around the margin of the Zuñi depression, the relative bulk is small and the materials are waterlaid. The most reasonable hypothesis appears to be that the depression is due to the sinking of its bottom, and the fact that there are salt springs and the area is underlain by salt-bearing beds are significant in this connection. It seems possible that a salt bed has been dissolved, possibly by hot water issuing from a volcanic vent, and the depressed area has dropped or faulted several hundred feet. Several instances are known of the development of deep crater-like depressions due to underground solution of salt and

gypsum beds, and sinking of overlying strata, notably at the "Salt Lake" near Meade, Kansas, and the "Devil's Hole" near the River Virgin in southwestern Utah. At the Zuñi salt lake, however, volcanic phenomena appear to be connected with the development of the depression, especially the presence of cinder cones in the center and the mantle of stratified ejecta encircling its rim. Probably the lava sheet capping the east rim is older than the

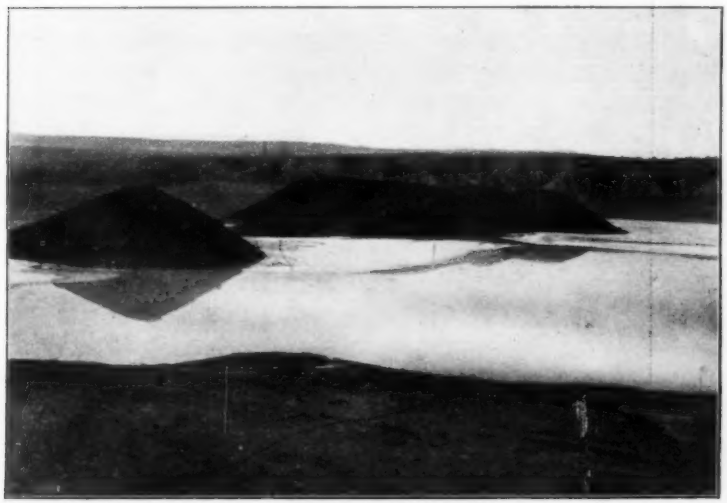

FIG. 4.—Looking southwest across Zuñi salt lake. Large cinder cone to the right, small cinder cone to the left, rising out of salt fields. South rim of depression in middle-ground, plateau of Cretaceous sandstone in distance.

depression, and perhaps did not come from the same orifice as the cinder cones. In the plateau region of New Mexico such cones are usually built following an outflow of lava and mark the last stage of the eruption. The cones in the depression appear to be very fresh and recent, and while they may be connected with a lava flow under the floor of the depression, there is no evidence on this point. The following hypothesis as to the origin and history of the Zuñi salt lake depression lacks positive evidence along several lines, but it is the most plausible one suggested.

Originally the area was a plain sloping gently to the Carrizo Creek and on this plain a sheet of lava was ejected, possibly from a vent marked later by the cinder cones in the depression. Following the

FIG. 5.—Looking into the crater in the larger cinder cone; showing pool of salt water which is at lake level.

lava flow there was a great ejection of hot water from a central vent, which dissolved a thick mass of salt, and brought to the surface and spread in all directions a large amount of fine scoria and rock frag-

ments, including the fossiliferous limestone. By this means a great, low mound of irregularly stratified material was built, extending from the edge of the depression. Consequent upon this eruption, a circular depressed area, a mile in diameter, subsided into the space made by the solution of salt and in smaller measure by the ejection of various rocks.

A much less probable hypothesis is that not only the lava sheet was extruded, but the sheet of volcanic ejecta was deposited and the cones built up *prior* to the subsidence. If this was the case, there is under the floor of the depression a sheet of lava overlain by a thick mass of volcanic ejecta, faulted down from the level of the lava and ejecta deposits on the rim. After the subsidence a new eruption gave rise to the cinder cones, at least to the one with the crater, for the other cone northeast may represent the stock of an earlier eruption. Water has continued to rise in the bottom of the depression, now only in small volume, but carrying much salt. Probably the lake occupied the entire bottom of the depression at one time, but evaporation and sediments especially those deposited by the torrential water courses on the south side, have evidently diminished the water area.

THE TERTIARY HISTORY OF THE TENNESSEE RIVER

DOUGLAS WILSON JOHNSON
Massachusetts Institute of Technology, Boston

CONTENTS

INTRODUCTION.
LITERATURE.
THE PROBLEM STATED.
EVIDENCE IN FAVOR OF THE THEORY OF CAPTURE.
The Coosa-Tennessee divide.
Volume of material eroded and deposited.
Youthful character of the gorge.
Distribution of the Unionidæ.
SUMMARY OF EVIDENCE IN FAVOR OF THE THEORY OF CAPTURE.
EVIDENCE IN FAVOR OF THE ALTERNATIVE THEORY.
The winding character of the gorge.
Stream dissection north and south of the gorge.
The divide south of Chattanooga.
Insufficient inequality of levels.
Absence of Tertiary gravels south of Chattanooga.
SUMMARY AND CONCLUSIONS.

The following paper was presented as a thesis in a graduate course in physiography at Harvard University in June, 1904, on the basis of a study of previous essays concerning the Tennessee River, a review of the general problem of river-capture, and an examination of the district about Chattanooga during a two-weeks' excursion in April, 1904. The writer is under obligations to Dr. C. Willard Hayes, Mr. Marius R. Campbell, and others, for numerous courtesies extended in connection with both field and office work.

INTRODUCTION

The Tennessee River, after flowing southward through a broadly open, longitudinal valley for some distance in the eastern part of the state of Tennessee, to a point near the city of Chattanooga, turns abruptly westward through a deep, narrow, winding gorge, which

is cut in the high, flat-topped mountain known as Walden Ridge; and then bends southward again in a longitudinal valley similar to the one it occupied before entering the gorge. Both of the longitudinal valleys are opened on anticlines of easily eroded limestone, while the transverse gorge cuts across a shallow syncline of resistant sandstone underlain by limestone. The turn of the river from the

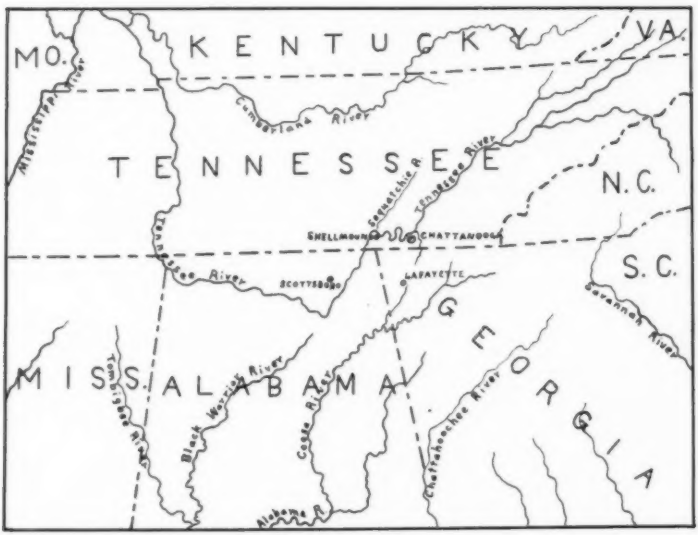

FIG. 1.— Location map.

broad longitudinal valley abruptly westward through a high mountain barrier presents a problem that has interested physiographers for some time.

Two hypotheses have been advanced in explanation of this problem. According to one, the river acquired this course across the mountain some time before the close of the Cretaceous period of baseleveling, probably near the close of that period, when the present flat top of the mountain was continuous with the rest of the Cretaceous peneplain; after later uplift the river continued to flow in that course throughout the Tertiary and Recent cycles, cutting its narrow transverse gorge below the level of the Cretaceous peneplain at the

same time that the broad longitudinal valleys in softer rock were being excavated. According to the other hypothesis, throughout the Tertiary cycle the river flowed on southward in the longitudinal valley east of the mountain, and so, by way of the Coosa and Alabama Rivers, into the Gulf of Mexico, continuing in this course until the present broad valleys both north and south from Chattanooga were completed (Fig. 2); then, at the close of the Tertiary cycle, by a process of stream capture, the Tennessee was tapped at a point near Chattanooga by a branch of a stream occupying the valley west of the mountain, and so diverted from the former course to its present course through the gorge (Fig. 3). In recent years this latter theory has been most strongly supported. Certain new evidence, now available, appears to afford good reasons for adopting the first of these theories. It seems desirable, therefore, to review the previous considerations of this problem, weighing carefully the evidence both for and against each theory.

LITERATURE

In 1894 there appeared a paper by C. Willard Hayes and Marius R. Campbell on *The Geomorphology of the Southern Appalachians.* Their essay gives a somewhat detailed account of the physiographic history of the region treated, and devotes a number of pages to the Tennessee drainage problem. The results of their studies led them to believe in the post-Tertiary diversion of the Tennessee from a former southward course; hence they support the second of the above hypotheses with a variety of evidence. This evidence is discussed in detail below.

In a later paper, on *The Physiography of the Chattanooga District*, Dr. C. Willard Hayes discusses the physiographic development of the region more fully than in the former paper by himself and Mr. Campbell. Dr. Hayes traces the past history of stream-adjustments throughout the region in great detail, offering a new interpretation regarding one or two points in the Tennessee problem, but supporting the main conclusion reached in the earlier report.

In 1900 Mr. Charles T. Simpson published a paper on *The Evidence of the Unionidæ Regarding the Former Courses of the Tennessee and Other Southern Rivers.* Working along entirely

different lines, Mr. Simpson independently came to the same conclusion as that reached by Messrs. Hayes and Campbell, supporting the second of the two hypotheses already referred to, on biological evidence alone. This came as a most striking confirmation of the work of Hayes and Campbell, and the paper created much interest. The biological evidence is given in greater detail in Mr. Simpson's monograph on *The Naiades, or Pearly Fresh-Water Mussels*. The nature of this argument is considered below.

In 1901 Mr. Charles C. Adams accepted the theory of capture as set forth by Messrs. Hayes and Campbell, explaining upon the basis of this theory certain faunal peculiarities of the region in question. Mr. Adams' paper, entitled *Baseleveling and its Faunal Significance, with Illustrations from the Southeastern United States*, accounts for the differences existing in members of the same group of shells as found in the Tennessee and Alabama systems as being due to a separation of the group into parts by the diversion of the upper Tennessee at Chattanooga, and subsequent evolution of these two groups along somewhat different lines.

A recent number of the *Journal of Geology* contains an article by Mr. C. H. White on "The Appalachian River *versus* a Tertiary Trans-Appalachian River in Eastern Tennessee." Mr. White reviews the evidence presented by Hayes and Campbell, believes that it is not sufficient to prove the diversion of the Tennessee from a former southward course, and concludes in favor of the first of the hypotheses given above—that the river has occupied its present course across the mountain since the Cretaceous cycle. The biological evidence furnished by the Unionidæ is not considered by Mr. White, nor does he present direct evidence in support of his conclusions.

Professors T. C. Chamberlin and R. D. Salisbury, in their recent textbook on *Geology* (Vol. I, pp. 164-68), devote several pages to a presentation of the Tennessee problem as an example of river capture due in part to crustal warping.

THE PROBLEM STATED

Hayes and Campbell have shown that near the close of the Cretaceous period the region about Chattanooga had been reduced to a nearly featureless peneplain over which the streams wandered with

sluggish courses. The completion of this peneplain marked the close of the first physiographic cycle of which we have satisfactory evidence in the district. With the elevation of the region above sea-level at the beginning of the Tertiary, the second cycle commenced, during which the streams, flowing over weak rocks, were able to excavate broad valleys nearly to their headwaters, developing in these valleys a second plain of denudation, the Tertiary peneplain, while hard rock regions remained unreduced, preserving the Cretaceous peneplain over broad areas. This Tertiary cycle was followed by depressions and elevations, the final result of which has been to leave

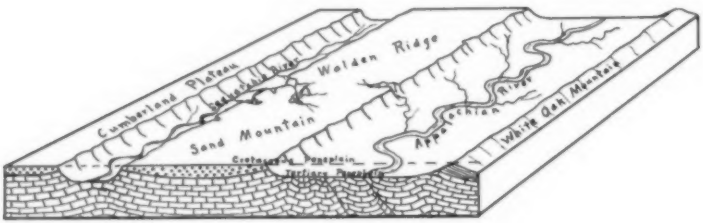

FIG. 2.—Supposed former course of Tennessee (as Appalachian).

the Tertiary peneplain well elevated and to allow the streams to cut their valleys some distance below its level. The elevations and depressions were accompanied by distinct warping, and the warping is correlated with certain drainage modifications (1894).

Dr. Hayes, in his report on the physiography of the Chattanooga district, gives specific names to the different peneplains, the Cretaceous peneplain being known as the Cumberland, the Tertiary as the Highland Rim, and a still later level, near the present beds of the streams, as the Coosa peneplain. We are not here concerned with the more exact ages ascribed to the several peneplains, nor with the last formed of the three, the Coosa. And since we are dealing with a particular problem, which is more fully discussed in the earlier paper by Hayes and Campbell, we will, for sake of convenience, employ the more general terms used in that essay.

In the accompanying figures (Figs. 2 and 3) the flat top of Walden Ridge, continued southward as Sand Mountain, represents a remnant

of the old Cretaceous peneplain. In the broad valleys on either side of this mountain was developed the Tertiary peneplain, remnants of which are still distinctly visible in places, although post-Tertiary erosion has destroyed much of its surface. Fig. 2 shows the supposed former course of the Tennessee as given by those who support the theory of capture. According to this theory, a great river, called the Appalachian by Hayes and Campbell, flowed southward past Chattanooga, across what is now the low divide near Lafayette, on south through this valley to the Coosa River, and thence by way of the Alabama River to the Gulf. In the Sequatchie valley, west of

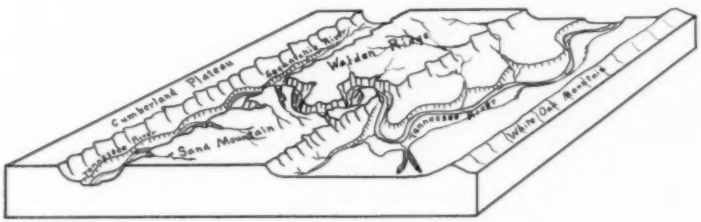

FIG. 3.—Present course of Tennessee River.

Walden Ridge, a parallel, southward-flowing, subsequent stream, the Sequatchie River, is believed to have occupied a level 100 feet lower than its neighbor to the east, thus having some advantage over the latter. It is conceived that near the close of the Tertiary period a branch of the Sequatchie worked headward through the ridge, finally tapping the Appalachian River at a point near the present site of Chattanooga, and diverted its waters westward down through the gorge to the lower level of the Sequatchie valley, thus giving birth to the present Tennessee River. The broad valley southward from Chattanooga, being thus deserted by the upper Appalachian River, was left to the occupancy of the shrunken lower portion of that beheaded stream, and a small tributary of the new Tennessee River (Chicamauga Creek and its branches) succeeded in pushing the low divide which was first established at the point of capture southward along this valley nearly to Lafayette.

Opposed to this theory, which has as its essential feature a grand example of river-capture, is the conception that since the close of

the Cretaceous period, at least, the drainage relations in this region have been essentially as they now are; that the present valleys were carved by the streams which now occupy them; and that, so far as the time element is concerned, all of these valleys are of practically the same age, no recent capture having taken place.

Previously to the appearance of Mr. White's paper, above referred to, and before I was aware that he was interested in the Tennessee problem, I became convinced that the evidence presented by Messrs. Hayes and Campbell, and by Mr. Simpson, while very suggestive, was not conclusive. Being at the time interested in the study of river-capture in general, I was in hopes that an examination of the Chattanooga district with this particular drainage problem in mind might result in securing certain evidence which would throw additional light on the question. Accordingly, in April, 1904, the region was visited, and a brief study made of the winding gorge; the river above and below the point of supposed capture; the divide between the Tennessee and Coosa drainage south of Chattanooga, and the small streams flowing north and south from this divide; the Sequatchie River in the valley west of the mountain, a branch of which is supposed to have effected the capture; and the valley southwest of Scottsboro, Ala., which has been contrasted with the gorge of the Tennessee. Certain facts were noted which seemed to indicate that the Tennessee River has occupied its present course since the Cretaceous period of baseleveling, instead of having been diverted westward by a comparatively recent capture; and which seemed to explain satisfactorily the peculiar features of the gorge on the basis of this hypothesis. Since this evidence would lead to a conclusion so radically different from that reached by former students of the problem, it is desirable carefully to consider both lines of evidence—that in favor of the theory of capture, as well as that in favor of the alternative theory.

EVIDENCE IN FAVOR OF THE THEORY OF CAPTURE

Hayes and Campbell base their conclusions, that the southward-flowing Appalachian River was captured near the site of Chattanooga by a branch of the Sequatchie River, upon the three following lines of evidence: (1) the character of the divide between the Tennessee

and Coosa-Alabama drainage basins; (2) a comparison of the amount of material eroded from the Appalachian valley with that of the sediment deposited at the mouth of the Coosa-Alabama River; (3) the character of the gorge of the Tennessee below Chattanooga.

Evidence from the Coosa-Tennessee divide.—Regarding the character of the divide between the Tennessee and Coosa-Alabama basins, Hayes and Campbell point out the fact that the divide is low and indistinct, and that it occurs as a less prominent feature in the well-defined, broad, open valley which is continuous to the northeast with the valley of the present Tennessee above Chattanooga, and to the southwest with the valley of the present Coosa and Alabama Rivers. The well-marked character of this broad valley, which continues directly across the dividing line between the two river basins, is thought to indicate the former presence of a large northeast-southwest stream, the Appalachian River. This being true, the present position of the large stream must have resulted from river-capture, and a diverting stream must have led the upper Appalachian westward through the new-made gorge.

It does not seem to me that the baseleveled character of the divide alone necessitates the conclusion that a large stream once flowed across it. In order to make such a conclusion necessary, we should have to assume that every such broad valley developed across a low divide must have been carved by a large stream—an assumption which does not seem to be warranted. The region is one of parallel bands of alternating hard and soft rocks. (This parallelism of structure would prevent the development of dendritic drainage, the absence of which is noted by Hayes and Campbell.) The soft bands are rapidly eroded, while the hard bands remain as intervening ridges. Thus the region is characterized by broad, northeast-southwest valleys, many of which are occupied by very insignificant streams between whose headwaters are inconspicuous divides. Nor does there seem to be any need of assuming the former presence of larger streams, since the softness of the rocks and their easy solubility sufficiently account for the phenomena observed. Indeed, there are cases in which it seems practically certain that no drainage readjustments have taken place in recent geological time. Hayes and Campbell recognized this fact, and, after stating the argument and their

conclusion, added another paragraph in which they said that, while they formerly regarded the argument as conclusive, further study of other similar divides had led them to modify this opinion. They cited the divides between the Potomac and James, and between the James and Roanoke basins, as cases similar to the one in question, but where there was no reason, so far as known, for supposing that a large stream ever existed. Evidently, then, this one of the arguments is only of negative value; it is permissive, but in no wise conclusive. That in this particular case the divide really presents features which make it difficult to conceive how a large stream could ever have flowed across it, is pointed out in subsequent pages.

Evidence from the volume of material eroded and deposited.—The second line of evidence developed by Hayes and Campbell is as follows: If we can ascertain the quantity of sediments carried out by the Alabama River system during Tertiary times, and can also ascertain the quantity of material eroded from the basins of the Coosa-Alabama system and the upper Tennessee system during Tertiary times, we can then compare the two results and find out whether the amount of sediments deposited is balanced by the amount of material eroded from the Coosa-Alabama basin alone, or whether it is only balanced when we add to it the material eroded from the upper Tennessee basin also. Lines are drawn midway between the Alabama and the Chattahoochee on the east, and between the Alabama and Tombigbee on the west, and all the Tertiary sediments between the two lines regarded as the material carried out by the Alabama system in Tertiary times. The amount is estimated at 2,340 cubic miles. Turning now to the amount of material eroded from the basin of the present Alabama system during Tertiary times, a careful estimate places the amount at 622 cubic miles. It is evident from these figures that some other area must have contributed to the formation of the vast amount of sediments laid down opposite the old mouth of the Alabama. If we add to the material eroded from the basin of the present Alabama system the material eroded from the basin of the upper Tennessee system, it is found that the total material eroded from both basins, during Tertiary times, is about 2,500 cubic miles. This agrees closely enough with the 2,340 cubic miles of Tertiary sediments found opposite the old mouth of

the Alabama River. It follows from this that the Upper Tennessee basin must formerly have drained out through the Coosa-Alabama system by a river occupying the old valley across the divide south of Chattanooga, that stream having since been diverted westward through Walden Ridge by a branch of the Sequatchie River.

If all of the sediment laid down in the sea opposite a given river is brought there by that river alone, then this evidence would indeed seem conclusive in favor of the theory of capture. It is believed, however, that such an assumption would be contrary to what we know regarding the behavior of river-brought sediment under marine control. It would imply an absence of all appreciable transportation and distribution under the action of oceanic and littoral currents, the well-recognized drift to leeward produced by storm-waves, and the small but long-continued action of the tides. That these agencies have a very important influence seems well established by a large number of concrete observations. According to LeConte, the sediment brought down by the Amazon is carried seaward by a strong tide, taken up by the ocean currents, swept to a distance of 300 miles or more, and much of it deposited on the coast of Guiana (p. 40). It is estimated that the Nile carries out past its delta 36,600,000 cubic meters of silt every year. Yet this enormous amount of sediment apparently does not add to the seaward extent of the delta, because of a powerful marine current that sweeps past the coast and transports the sediment far eastward, where it is finally thrown down along the coast of El Arich desert. Over a portion of Blake plateau, southeast of Georgia, between depths of 100 and 600 fathoms, the bottom seems to be swept clean of mud, ooze, and almost so of living species. Agassiz attributed this to current action. And, again, LeConte tells us that the sediments brought into the Gulf of Mexico by the Gulf rivers are swept along by current action, and in part deposited on Florida Point, and the Bahama Banks (p. 40), while Mr. White (p. 36) refers to the fact that "after the formation of the Nita Crevasse in 1890, fine mud from the Mississippi was deposited in Mississippi Sound even up to the mouth of Mobile Bay, driving out the fish and killing the oysters" (E. A. Smith *et al.*, p. 30). Account must also be taken of the numerous well-recognized cases of transportation due to the set or drift given by storm-made waves and

currents. Dana records the drifting of large quantities of coal and brick from wrecked vessels many miles from where they were dropped (p. 224). An anchor with ten fathoms of chain attached was carried one and a half miles in three weeks (p. 225). The effect of such storm-made waves and currents on small gravel, sand, and the finer sediments must be profound. Coarse gravel on Moray Firth is drifted eastward for over fifteen miles (Geikie, p. 418); the ground-swell off Land's End washes cobbles weighing as much as one pound into lobster pots at a depth of thirty fathoms (Douglas, quoted by Geikie, p. 419). Much of the material forming the great barrier beaches along the Atlantic coast is believed to have been brought from considerable distances. As a result of the strong southward drift along the coast of the southeastern United States, according to Professor Bache, the siliceous sands are carried the whole length of the limestone coast of Florida (LeConte, p. 36). Dana tells us that the large amount of sediments brought to the sea by all of the rivers of the Atlantic coast is *widely* distributed (p. 224). It is believed, then, that however closely the estimates of material eroded from a river basin and of material found opposite the mouth of that river agree, or how widely they may disagree, no conclusions as to the former extent of those river basins can be rightly based on such estimates, in the face of the strong probability, amounting almost to a certainty, that an unknown amount of sediments carried out to sea by that river have been transported by marine action beyond the area in front of the river, while an unknown amount of sediments brought out by other rivers has been carried into that area.

There are still other considerations which seem to place difficulties in the way of accepting this line of argument. As Mr. White has pointed out, a large proportion of the sediments in question is of limestone, containing quantities of corals and other fossils (E. A. Smith, *et al.*, pp. 226–31). It is not believed that the Alabama River can properly be held responsible for those deposits which are transported in solution and in a very finely divided state, and which may originally have come, in part at least, from far-distant rivers. Mr. White notes still another objection to this argument in the following words:

> The thickest and most important of the beds attributed to the Appalachian River, the Lignitic (900 feet), is composed of cross-bedded sands and clays, and

would seem, at first sight, more than all others, to have been deposited by this river; but a study of the whole area shows that this formation increases in thickness and coarseness toward the west, in western Alabama and in Mississippi; while east of the Alabama River it is very calcareous and inconspicuous, showing that these sandy sediments were brought down from the west instead of from the north (p. 36).

In view of the considerations stated above, it is not believed that any argument in favor of the supposed capture of the Appalachian River by a branch of the Sequatchie can be properly based on a comparison of the sediments opposite the mouth of the Alabama River with the amount of material eroded during Tertiary times from the basin of the Alabama or other rivers. So far as such evidence goes, there seems to be no reason for supposing that the Coosa-Alabama River was ever any larger than it is now.

Evidence from the character of the gorge below Chattanooga.—The third line of evidence developed by Hayes and Campbell in favor of the diversion of a southward-flowing Appalachian River by a branch of the Sequatchie River to the west, is based on the youthful character of the transverse gorge west of Chattanooga. They recognize the fact that the course of the river through a ridge capped by hard sandstone several hundred feet in thickness would necessitate, on the basis of either theory, a valley of younger expression at this point than east or west of it where the river follows weak rocks. Their argument is that the *degree* of youthfulness is too great to be accounted for on any other theory than that of a comparatively recent diversion of the river to that course by a process of stream-capture. This is a point which does not readily admit of demonstrable proof, and the best evidence is to be secured from a comparison with other valleys of known age and formed under similar conditions. Hayes and Campbell, therefore, compare the gorge of the Tennessee through Walden Ridge with a valley southwest of Scottsboro, Alabama, in the following words:

While a direct comparison cannot be made between the Walden gorge and the upper Tennessee valley on account of difference in conditions, such a comparison can be made between the gorge and a valley in northern Alabama, extending from Scottsboro southwestward to the mouth of Flint River. . . . . It is nowhere less than six miles broad, and its floor is very regular, forming a portion of the Tertiary peneplain. The age of this valley is easily determined; it is carved in the Cretaceous peneplain; therefore it is more recent than the Cretaceous;

it is continuous with the Tertiary peneplain, and hence was complete at the close of the Tertiary baseleveling period; and at the close of that period it was deserted by the stream which carved it. The conditions under which this valley was cut are practically the same as those now prevailing in the gorge through Walden plateau. In both cases the rocks are nearly horizontal, heavy sandstones capping the plateau, with easily erodible Carboniferous limestones beneath. Such conditions are highly favorable for rapid corrasion of a river channel. The sandstone cap is undermined, and its débris rolls down and forms a talus on the lower slopes. The rate at which the cliffs recede depends largely on the rate at which the sandstone talus is removed from the slopes and the limestone is exposed to erosion. No conditions could be more favorable for this rapid removal of the protecting débris than those now present in the Walden gorge, where the base of the slope is washed by a stream competent to remove all talus from the cliffs above, the coarsest as well as the finest. Certainly the conditions in the gorge are fully as favorable as they were in the valley west of Scottsboro when that was being cut, and the stream which flowed in that valley was probably smaller than the present Tennessee; therefore, if under the same conditions a smaller stream than the present Tennessee could cut so broad a valley as it did in northern Alabama during the Tertiary cycle, the conclusion seems inevitable that the present gorge through Walden plateau has been occupied a very much shorter time, and hence the Appalachian drainage was not diverted to its present westward course till after a part or the whole of the Tertiary cycle (pp. 113, 114).

While a comparison of the Tennessee gorge with some valley of known age may be expected to give us our best light on this particular phase of the question, two very serious criticisms must be urged against the comparison given above. In the first place, sufficient account is not taken of the details of geological structure in the two regions compared, although these details are features of prime importance in the present connection. In the second place, the comparison is one between the *Tertiary* valley southwest of Scottsboro and the *present* gorge of the Tennessee. The references are always to "the present gorge through Walden plateau," the conditions "now prevailing in the gorge," etc. A proper comparison can only be made between the Scottsboro Tertiary valley and the gorge of the Tennessee *as it also appeared at the close of the Tertiary period.*

When the geological formations in the region of the Scottsboro valley and in that of the Tennessee gorge are compared, it is found that the conditions under which the two valleys were carved were far from being the same. It is true that in each case we have soluble limestone capped by hard sandstone, but the sandstone cap in the

two cases is of very different thickness. An examination of the Sewanee, Stevenson, and Gadsden folios of the United States Geological Survey shows that the sandstone covering thins out toward the Scottsboro region, this thinning being due in part to an original westward thinning of the beds, but more especially to the beveling of the successive formations by the Cretaceous peneplain, represented by the plateau tops. The Walden sandstone disappears entirely over much of the Sewanee area, northeast of the Scottsboro sheet, so that the underlying Lookout sandstone alone is represented on many of the plateau remnants; and while in the Stevenson and Gadsden regions the Walden sandstone covers a greater area, it is markedly thin, even on Sand Mountain, where the underlying Lookout sandstone comes to the surface over considerable areas, probably in part the result of a shallow synclinal fold. Over that part of the Stevenson region immediately northeast of Scottsboro, the Walden sandstone is wholly absent, and only a thin layer of the Lookout sandstone caps the plateau remnants. So, while we have no folio of the Scottsboro region itself, the conditions over the adjoining districts are such as to lead us to expect a much thinner cap of the sandstone over the lime about Scottsboro than in the vicinity of the Tennessee gorge. An examination in the field proves this to be the case. Just what the difference in thickness of the sandstone cap is in the two cases is difficult to determine with accuracy, owing to the fact that the limestone readily weathers out from under the overlying sandstone, allowing fragments of the latter to drop down and mantle the mountain slopes, thus concealing the limestone and making it harder to ascertain its true thickness. The tendency is to underestimate the thickness of the limestone, and correspondingly to overestimate that of the sandstone. But even if we assume the maximum possible thickness of sandstone over the Scottsboro region, and the minimum thickness over the region of the Tennessee gorge, there is still shown to be a markedly greater thickness at the latter place than at the former.

Ten miles southwest of Scottsboro the valley has its normal development, and the adjacent plateau remnants are well shown. Here, as elsewhere, the valley is seen to be cut largely in limestone, which shows conspicuously on the mountain slopes. Limestone float is

abundant all along the foot of such slopes, and comparatively little sandstone is seen. Two sections in this vicinity showed the practically continuous limestone ledges up to within 190 feet of the top of the plateau or mountain. For reasons stated in the preceding paragraph, it is highly probable that the limestone continues still higher, no sandstone ledges being seen until nearer the top, and sandstone débris mantling the slopes for some distance. But even if we ascribe the entire thickness of 190 feet to the sandstone, the contrast with conditions at the Tennessee gorge is very marked. North of Scottsboro it appears that the sandstone cap was somewhat thicker, suggesting a progressive thinning toward the western end of the valley, although the possibility that the limestone goes higher up the slope than is apparent makes a definite statement impossible. Such a westward thinning would be in accord with the indications on the geologic folios of adjacent areas, however.

Turning now to the conditions at the winding gorge through Walden plateau, we find plenty of evidence that the gorge is cut largely in sandstone. Instead of conspicuous limestone ledges well up the mountain slopes, we find the slopes mantled with coarse sandstone débris, generally down to the level of the river. Only near the eastern and western mouths of the gorge was the limestone shown at all prominently, and this is where the gentle rise of the sides of the synclinal trough would naturally bring the limestone to a higher level; while in the Scottsboro valley the limestone is everywhere prominently shown well up toward the plateau summit. Limestone is shown at various other points throughout the gorge, but always, so far as seen, in limited exposures well down at the foot of the slope. Limestone float was little in evidence, usually only close to the small ledges referred to, sandstone débris being everywhere abundant. Although the limestone was undoubtedly greatly masked by the sandstone débris, exposures of the limestone on the spurs of the mountain, and the careful examination of float and ledges along the courses of side streams emptying into the gorge, indicated that in the main portion of the gorge the limestone-sandstone contact could not be far above the level of the river. In the half-dozen best sections seen, the limestone exposures or limestone débris always stopped short at elevations of between 100 and 200 feet above the

river. The limitation of the limestone to the bottom of the gorge is also indicated by the presence of sandstone in ledges apparently in place well out on spurs projecting forward from the main base of the mountain. These spurs occupy a position which does not seem to admit of their sandstone being interpreted as débris that had been let down from above by the undermining of the limestone.

The geological map accompanying the Chattanooga folio represents a larger portion of the gorge as being in limestone. Thus the thickness of the limestone exposed in the gorge is shown as over 600 feet in places, and as less than 300 in others. Throughout a large part of the central portion of the gorge the 1,000-foot contour line is taken as the upper limit of the limestone, and the indicated thickness of between 300 and 400 feet of limestone may be taken as a fair average figure as given by this line of evidence. This leaves, as the map shows, a cap of between 600 and 700 feet of sandstone.

It appears, then, that if we take the more conservative estimates of the thickness of sandstone in the Walden gorge, the sandstone cap at that locality is still over three times as thick as the similar cap in the Scottsboro valley. If a thickness of sandstone be taken nearer that indicated by the sections given in a preceding paragraph, the contrast is still more marked. Such a difference in geological structure must result in a marked difference in form between the two valleys. The Scottsboro stream, having the thin cap of hard rock to cut through must have reached the underlying soft rock, and so have had ample opportunity to widen its valley under favorable conditions, while the stream through Walden gorge, having the thick cap of hard rock to contend with, still continued for a long time to carve a narrow gorge in the resistant beds. The great degree of contrast to be expected in this particular case will be more apparent after a consideration of the next point.

A second serious objection to the comparison between the valley southwest of Scottsboro and Walden gorge is found in the fact that it is throughout a comparison between the former as it was at the end of Tertiary times, and the latter as it is at present. As Hayes and Campbell have shown, the Scottsboro valley was completed at the end of the Tertiary period, and the valley floor forms a part of the

Tertiary peneplain. It has not been materially modified since, and therefore it is truly a Tertiary valley. On the other hand, while the Tennessee gorge had a certain form at the close of the Tertiary period, post-Tertiary cutting has lowered the gorge 250 feet, almost obliterating all traces of the old Tertiary valley floor at the higher level. Manifestly, then, the two valleys as they are at the present cannot be properly compared. The comparison becomes of value only if we conceive the post-Tertiary cutting in the gorge to be replaced, filling up the bottom of the gorge to the level of the Tertiary peneplain. We may then compare the two valleys as they were at the close of the long period of Tertiary baseleveling. Such a comparison shows a more marked contrast in geological conditions in the two valleys than that already indicated.

Hayes and Campbell have shown that the Tennessee River at Chattanooga has cut down its channel 250 feet below the level of the Tertiary peneplain, while the distribution of the Tertiary gravels, to be considered later, indicates that the gradient of the river through the gorge was then much the same as now. Hence filling up the gorge to that old level, and thus restoring the Tertiary peneplain, means a reduction of 250 feet in the extent to which the river had cut into the limestone then as compared with now. And since the vertical extent of limestone now shown in the gorge is between 300 and 400 feet, according to the larger estimates, this means that at the close of the Tertiary baseleveling period the Tennessee had cut into the limestone underlying the massive sandstone cap only between 50 and 150 feet; while if we accept the smaller estimates for the thickness of the limestone exposed at present throughout the main portion of the gorge, which seems to the writer to be nearer the actual conditions, we find that at the close of the Tertiary the river was in places still flowing wholly in sandstone, not having yet reached the underlying limestone. At this same time the stream southwest of Scottsboro had cut through the thin sandstone cap of that region and over 400 feet into the underlying limestone. The following figures illustrate graphically the different conditions obtaining in the two areas at the close of the Tertiary baseleveling period.

These diagrams are based on the more conservative figures given above. It is believed that the actual conditions at the close of the

Tertiary period would be more accurately represented by making the sandstone cap over the limestone of the Scottsboro valley (Fig. 4) thinner than it is shown, and the sandstone of the gorge (Fig. 5) enough thicker to show the gorge entirely in sandstone.

FIG. 4.—Section of Scottsboro valley showing relations of sandstone cap and underlying limestone at close of Tertiary cycle (same as at present). (Horizontal scale, 1 inch = 1 mile. Vertical scale, 1 inch = 2,000 feet.)

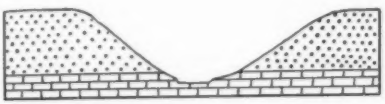

FIG. 5.—Section of Tennessee gorge showing relations of sandstone cap and underlying limestone at close of Tertiary cycle. (Scale, same as in Figure 4.)

But even on the basis of the more conservative representation, the contrast in conditions under which the two valleys were carved is such as to explain satisfactorily the difference in form which has been noted. Indeed, it is difficult to conceive how the gorge of the Tennessee could be otherwise than narrow and steep-sided as compared with the Scottsboro valley, since it was carved almost wholly, or possibly entirely, in hard sandstone throughout the long period of Tertiary baseleveling, and only during the comparatively very short post-Tertiary trenching have favorable valley-widening conditions existed; whereas the Scottsboro valley was carved largely in easily erodible limestone, favorable conditions certainly existing a vastly longer period in this case. It appears, then, that the gorge of the Tennessee might be more properly compared with other gorges cut through sandstone ridges since the Cretaceous period, such as those of the Delaware and Susquehanna Rivers through the Pennsylvania ridges; for while the present conditions at Walden gorge and the latter localities are different, they were much the same until comparatively recent times, barring the greater width of the Walden ridge, and a possible difference in hardness of the sandstone.

The degree of similarity between these gorges (Fig. 6) is what we should expect when the conditions under which they were carved were for so long a time so much alike; and inferences drawn from such a comparison seem more reliable than those from a comparison with a valley where the conditions were for so long a time so radically different. No comparison between the gorge through Walden Ridge, and the broad longitudinal valleys east and west of the ridge, can be made, since the latter were carved entirely on broad bands of soft rocks.

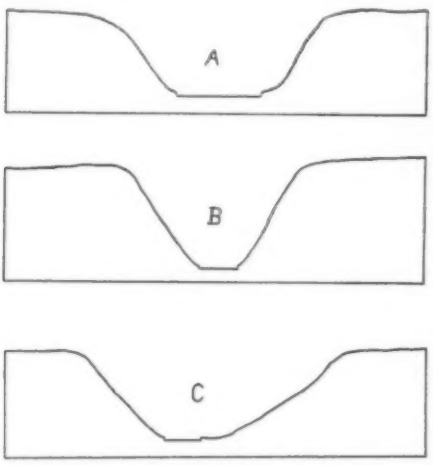

FIG. 6.—Profiles of (A) Susquehanna Watergap above Harrisburg through Second Mountain, (B) Delaware Watergap, and (C) Tennessee gorge. (Horizontal scale, 1 inch = 1 mile; vertical scale, 1 inch = 2,000 feet.)

It is believed, then, that when the geological conditions at the Walden gorge and the Scottsboro valley are carefully considered, and the comparison between the two made on the same time basis, the difference in form between the two will afford no evidence in favor of the recent diversion of the Tennessee River to a westward course. It is further believed that these considerations fully explain the present narrowness of the gorge on the basis of the alternative theory, the youthful features being just what we must expect under the conditions that have controlled erosion at this point since Cretaceous time.

Evidence from the distribution of the Unionidæ.—Six years after the publication of the paper by Hayes and Campbell giving the above lines of evidence, and the conclusions to which they led, Mr. Simpson reached the same conclusions from a study of the freshwater mussels of the region. The facts that Mr. Simpson brought forth are as follows: *Pleurobema*, a genus of Unio, has its metropolis

in the Tennessee River. It is not found throughout the other portions of the Mississippi basin. But it is found abundantly in the Coosa and Alabama Rivers. Also certain other forms of Unio common to the Mississippi-Tennessee basin are found in the Coosa-Alabama basin. From these facts Mr. Simpson concludes that at some time the upper Tennessee River must have flowed southward into the Coosa-Alabama River, since, to quote his words, "these forms cannot travel overland from river to river, but must have water communication in order to pass from one stream to another."

Mr. Simpson's argument in favor of the theory of capture is based on the assumption that the fresh-water mussels must have direct water communication (evidently meaning direct fresh-water communication) in order to pass from one stream to another. It appears that the recorded observations of many naturalists, and the facts of Unionidæ distribution, are both contrary to this assumption. In the first place, there are so many authentic cases where birds, insects, etc., have been taken with fresh-water shells attached to them, that students of the subject are compelled to believe in this method of dispersion of these forms from place to place. Darwin proved that young mollusks just hatching will attach themselves to the feet of a duck, and remain alive in this position out of water from twelve to twenty hours (p. 174). Mr. Arthur F. Gray, of Danversport, Mass., had in his possession the foot of a waterfowl to which was attached a bivalve shell. Canon Tristran shot a bird in the Sahara which had attached to it the eggs of some mollusk. Some shells attach themselves to plants which are carried away by birds (Darwin, p. 174). Insects are frequently taken with shells attached. There are at least five recorded cases of the capture of the water scorpion, *Nepa*, a large flying-bug, with small shells attached. The great water beetle, *Dytiscus*, is known similarly to aid in the dispersion of fresh-water Mollusca. The same is true of *Dineutes*. Mr. Albert P. Morse, of Wellesley, has kindly shown me specimens of these last two forms having attached shells. *Notonecta* has likewise been proved to carry these forms from place to place. Some of these insects are powerful flyers. Darwin records the capture of one of them out at sea, 45 miles from the nearest land (p. 174). Beddard, Kew, and other students of zoögeography regard birds and insects

as undoubtedly important agents in the dispersion of fresh-water shells. Woodworth catalogues a number of agencies recorded as aiding in this dispersion, in addition to those mentioned above (pp. 214–17). It appears, then, that other means besides river-capture for the passing of fresh-water shells from one stream to another are not lacking. That these means are efficient is proved by the distribution of these shells. Ponds are sometimes made by excavating a place where no water stands ordinarily, lining the excavation with concrete and allowing the rain to fill it. These ponds, for a time devoid of life, gradually become populated with mollusks and other shells, proving, as Beddard says, the capacity for active or passive migration on the part of the Mollusca. Careful and successive observations have proved in some instances the actual time in which a given pond may become populated. R. Ellsworth Call records the presence of a western species of Unio in a small isolated eastern lake, which was located down between high hills, fed by a mountain brook, and absolutely foreign to any stream through which the species might have been introduced.

But the most conclusive objection to Mr. Simpson's argument in favor of the theory of capture is found in the actual distribution of the very shells upon which he bases his argument. Mr. Simpson finds the genus *Pleurobema* in both the Tennessee and Coosa-Alabama basins. He says that in no case are the species in the two basins identical, but only similar. The basis of the argument, then, is similarity of forms; but if mere similarity of form proves former river connection, certainly identity of form should prove it with double force. Accordingly, we should not expect to find the same species of *Pleurobema* in any two rivers of this section whose location is such as to render practically impossible a former connection with each other, either directly or by way of intervening streams. An examination of Mr. Simpson's later monograph on the pearly fresh-water mussels (pp. 745–65) is of value in this connection. As will be seen, he records *Pleurobema similans* Lea, from Black Warrior and Cahawba Rivers, Alabama; and Pine Barren Creek, Escambia County, Florida. So far as can be judged from available maps, previous fresh-water connection between the former and the latter is extremely improbable. *Pleurobema strodeana* Wright is recorded from Escambia

River, Florida, and Flint River, Georgia. Any former connection in this case seems improbable. *Pleurobema harperi* Wright is recorded from Altamaha and Flint Rivers, Georgia; and Suwanee River, Florida. Here, again, connection between either of the former and the later seems out of the question. Other cases might be added—indefinitely, if we continue with other genera than *Pleurobema*. If we find it impossible to hold river-capture responsible for the distribution of identical species in all these cases, then mere similarity of forms in the Tennessee and Coosa-Alabama basins cannot be regarded as a valid argument in favor of river-capture near Chattanooga.

If we carry this line of argument to its logical conclusion, the objections to it become even more apparent. Mr. Simpson records one group of Unios as occurring everywhere in the streams draining into the Atlantic from Labrador to Georgia (1900, p. 134). If the occurrence of the *Pleurobema* in the Tennessee and Coosa-Alabama Rivers proves river-capture in that case, then the distribution just referred to must prove a great succession of river-captures from Labrador to Georgia. Nor is this all. The same species is in one instance found in Europe, northern Asia, Japan, northern North America, and Iceland (p. 677). According to the argument advanced, this means an inconceivable series of river-captures. Such violent hypotheses compel the conclusion that some other means than river-capture is commonly operative in effecting the distribution of fresh-water shells.

Certain features of Unionidæ distribution have led some to believe that their dispersal may take place by migration along the seacoast from one river system to another, as well as by the means already considered. Mr. Simpson evidently regards this as a possibility in the case of another instance of supposed river-capture (1900, p. 135), but does not consider it in connection with the more important problem of the Tennessee, unless certain statements near the first of his article are meant to imply such a consideration indirectly. He states that none of the *Pleurobema* are found in the lower 300 miles of the Mississippi River, in the Pearl or Pascagoula Rivers, or any of the small rivers in Mississippi or Louisiana flowing into the Gulf (p. 134). If it is meant to imply by this that no migration down the Tennessee to the Gulf, thence along the coast and up the Alabama and other

streams, could have taken place, because the intervening streams should, at the same time, have become populated by such a process, two answers may properly be made: (1) Such absence in the intervening streams is no more remarkable than that shown repeatedly in the distribution of the species of *Pleurobema* in the southern rivers, and of other forms elsewhere. (2) The migration along the coast may have taken place near the close of the Tertiary, at which time the rivers and portions of rivers referred to were not in existence. In this connection it is suggestive to note that, although Hayes and Campbell consider that the lower portion of the Tennessee River was diverted northward to the Ohio in recent time, not a trace of the Tennessee shells has been found to mark the supposed former southwestward course of the river through Mississippi.

The evidence recorded by Mr. Adams is much the same as that introduced by Mr. Simpson, except that Mr. Adams emphasizes more especially the *differences* existing between members of the same group found in the two river systems, and seeks to explain the differences by the proposed capture, whereas Mr. Simpson seeks to prove the capture by the similarity of these forms. It is believed that all of the phenomena noted are easily explicable independently of the theory of capture, and in this connection it is well to note that the presence of a longitudinal open valley across the low divide between the two basins is peculiarly favorable for the operation of some of the means of dispersal referred to above. The northward and southward migrations of birds along certain valleys are known, and where a low divide in a prominent valley alone separates the waters of two river systems it is to be expected that more or less mingling of forms will very likely take place.

In closing our consideration of this line of evidence, it is of interest to recall Mr. Simpson's statements regarding the dispersal of these shells, which appear in his paper on the *Distribution of North American Unionidæ*, published seven years prior to his Tennessee paper. In a footnote (p. 354) he observes:

> In many cases the Unionidæ seem to have had no difficulty in migrating across the country from river to river; an example of this being the Mississippi Valley species which now inhabit all the rivers of Texas, and some of those of eastern Mexico; while, on the other hand, species of South America extend up

into Central America. The embryos, in some cases, may be carried by aquatic birds in the manner elsewhere mentioned in this paper; in others, they probably migrate across overflowed regions near the sea, in time of floods.

Farther on (p. 358), in accounting for the presence of *Unio luteolus* in both the Missouri and Columbia Rivers, Mr. Simpson says:

I have traced it up the Missouri River to near its source, and when it is taken into consideration that the Marias, a tributary of this stream, heads within a few miles of Flathead Lake on Clarke's River, a branch of the Columbia, and that the embryos of Unios are provided with hooks by which they can attach themselves to the feet or feathers of aquatic birds, it is very easy to see how this species might have been carried from the waters of one drainage system to those of another.

Mr. Simpson does not consider the possibility of such means of dispersal when discussing the Tennessee problem, the whole force of his argument in that case lying in the statement: "These forms [the Unios] cannot travel overland from river to river, but must have water communication in order to pass from one stream to another."

It is believed, then, that the well-authenticated means of dispersal of Mollusca, and more especially the facts of Unionidæ distribution, are such as to render the argument in favor of the theory of capture, based on the evidence of the Unionidæ, invalid; for while it is believed that such a capture as has been proposed would result in the dispersal of the *Pleurobema* and other forms throughout the two basins, it is equally believed that other means of dispersal will account for all of the phenomena noted, some of which are inexplicable on the theory of capture alone.

SUMMARY OF EVIDENCE IN FAVOR OF THE THEORY OF CAPTURE

To review our consideration of the four lines of evidence in favor of the theory of a recent diversion of the Tennessee to its westward course through the gorge in Walden Ridge:

It has been shown that divides similar to that between the Tennessee and Coosa-Alabama basins exist in other regions at points where no large stream is ever supposed to have held its course. A consideration of the behavior of river-brought sediments under marine control, and of the character of the Tertiary sediments in Alabama, is believed to show the impossibility of properly basing any argument in favor of the capture on the comparison of sediments now exposed with

amount of material eroded. A study of Walden gorge and the Scottsboro valley shows the invalidity of any argument in favor of the theory of capture based on a comparison of the two valleys, and satisfactorily explains the narrowness of the gorge on the basis of an alternative theory. The supposed evidence of the Unionidæ in favor of the theory of capture is seen to be based upon assumptions which do not seem to be warranted by due consideration of the various means of molluscan dispersal or by the facts of Unionidæ distribution. It is therefore believed that the arguments brought forward in support of the theory of capture are far from conclusive, and that the history of the Tennessee is still open to consideration. Certain lines of evidence, some of which have hitherto been unconsidered, appeal to the writer as weighing strongly against the theory of capture, and as strongly indicating the continued presence of the Tennessee River in its present path across Walden Ridge since Cretaceous time.

EVIDENCE IN FAVOR OF THE ALTERNATIVE THEORY

The evidence against the proposed theory of capture, and in favor of the long continuance of the Tennessee in its present course through Walden Ridge, is derived from a consideration of (1) the winding character of the gorge; (2) the character of stream-dissection on the ridge both north and south of the gorge; (3) the character of the divide between the Tennessee and Coosa-Alabama basins, south of Chattanooga; (4) the lack of sufficient inequality of levels between the valleys east and west of Walden Ridge; (5) the absence of the Tertiary river gravels from the supposed former southward course of the river.

Before considering these lines of evidence which appear to bear directly on the present problem, it is desirable to note one line of evidence which might be available in certain cases, and to make clear my reasons for not applying it in the present instance. When a mature stream has developed a broad, open valley, the floor of that valley will have a gentle slope downstream, represented by the line *AD* in Fig. 7. Now, if capture of this stream takes place at a point *B*, the portion of the stream *AB* will intrench itself, developing a profile *A'B'*. From the point of capture, *B*, the divide will be pushed

in the direction of *D* to some point *C*, by what is termed the "inverted stream," whose profile is *B'C'*. It is possible that the profile *C'D'* may remain practically coincident with *CD*. In the interstream areas remnants of the old valley floor between *A* and *C* not yet destroyed by erosion will show surfaces which coincide with the prolongation of the line *CD* toward *A*.

On the other hand, if *C* represents a divide which has been long maintained, no large stream having flowed from *A* to *D*, then the

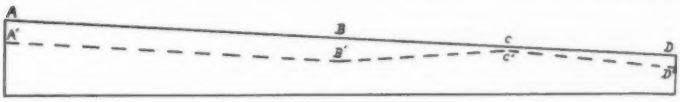

FIG. 7

profiles will be as represented in Fig. 8: streams flowing from *A* and *C* toward *B* to meet and find an exit from the valley developing the profiles *AB* and *BC*, while the stream flowing from *C* toward *D* developed the profile *CD*. Now, if the streams intrench themselves, remnants of the old valley floor in the interstream areas between *A* and *C* will show surfaces which do not coincide with the prolongation of the line *CD*. It may thus be possible, by a study of the inter-

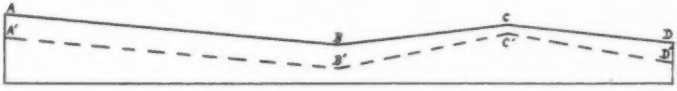

FIG. 8

stream spaces, to determine whether the present profile of the streams, *A'B'C'D'*, which is much the same in either case, is developed as a result of capture (Fig. 7), or merely represents the intrenching of streams which have long maintained their present general relations (Fig. 8).

The limited application of this test is evident. It would not apply to young streams with narrow valleys. It is equally obvious that if the streams had reduced their valleys nearly to baselevel, so that all slopes were very slight, and recent erosion had greatly dissected the former valley floors, the detection of the desired evidence might be impossible. In the case of the Tennessee drainage the streams had reduced their valley floors nearly to baselevel at the close of the

Tertiary cycle, and erosion subsequently to the uplift at the close of that cycle has been extensive. Sufficient time was not available for the work in the field necessary to prove whether or not this test was applicable, but it is not believed that satisfactory evidence of this nature is obtainable.

The winding character of the gorge.—In order to account for the winding character of the Tennessee gorge, those who support the theory of capture have been led to suppose a most complicated hypothetical series of drainage rearrangements. This series involves: the successive transference of divides from place to place along the headwaters of three or four separate streams, by a roundabout course some ten miles longer than that offered by the path of the stream supposed to be first encountered by the diverting stream; the removal of the massive sandstone cap throughout the courses of every one of those streams even to their headwater areas preparatory to the capture; and the definite localization of the axis of a broad, gentle uplift which is supposed to have determined the location of an assumed divide between the supposed contending streams. There are two difficulties in the way of accepting this explanation: It is impossible to accept the assumption that the several streams were able to breach the massive sandstone cap even to the divides between the streams, whereas much larger and more powerful neighboring streams, with all the advantage of post-Tertiary cutting, have scarcely begun to accomplish that work in their lower courses. This will appear more fully in a later paragraph. The proposed process of capture involves so much that is purely hypothetical that one is led to seek a less complicated explanation.

The winding character of the gorge is, on the other hand, what we should naturally expect if the meanders of the river are inherited from a former baseleveling period when the river meandered broadly over the site of the present ridge. Meanders which were developed when the river flowed with sluggish course over the Cretaceous peneplain would necessarily intrench themselves with some modification when the uplift occurred; and whatever the form of these meanders, no special and complicated explanation would then be necessary in order to account for each portion of the various curves. This more simple explanation finds confirmation in the succeeding lines of evidence.

Character of stream-dissection on Walden Ridge and Sand Mountain.—The streams occupying the open longitudinal valleys on either side of the ridge belong to that type known as subsequent streams, since they must have gained their present positions by a process of adjustment to weak structures from some former position more directly consequent upon the initial folding of the region. The branches of the subsequent streams which head up the ridge belong to the group of streams termed obsequent, since they have grown headward against the dip of the beds which they cut. It is one of the characteristics of obsequent streams that they are not located, so far as is known, by any specific structural factors, but develop at more or less regular intervals, as is required by the removal of rainfall. Over an area where practically uniform conditions prevail the development of such streams will be roughly uniform. We should not expect one stream of this class to dissect an area deeply, while similar adjacent streams had barely begun their work.

An examination of the Chattanooga and Stevenson topographic sheets shows that the dissection on Walden Ridge and Sand Mountain, north and south of the Tennessee gorge, has progressed at a fairly uniform rate. It also appears that the dissection is of no great extent, the integrity of the plateau remnant being quite well preserved in either direction. Only at the gorge is the flat-topped mountain cut wholly in two. Now, the theory of capture necessitates the assumption that one of the obsequent streams grew headward entirely through the mountain and cut down to the level of the main stream in the broad valley to the east, during the same time that its neighbors were able to make but a small beginning on the dissection of that mountain—an assumption which it seems difficult to accept. If one of the obsequent streams was able to cut its ways entirely through the ridge, then we should expect to find the ridge more or less nearly breached at various other points. This is distinctly not the case. The marked contrast between the amount of dissection at the gorge and elsewhere points to an entirely different origin for the gorge from that of breaching by an obsequent stream.

According to the suggested procedure of the supposed capture, the branch from the Sequatchie River to the west was aided in the breaching of the ridge by several small obsequents working back

into the ridge from the valley to the east. Such a process seems to add to the difficulties of the case rather than to decrease them; the disposal of the rainfall of a given area on the ridge by several streams instead of by one must mean less powerful streams and decreased cutting in each individual case. That such streams should have been able completely to breach the thick sandstone cap of the ridge, even at their headwater areas, by the close of the Tertiary period, whereas their larger neighbors, with the additional advantage resulting from 250 feet of post-Tertiary incision of the main streams, have only begun that process in their lower courses, seems wholly incredible. (In this connection it must be borne in mind that such streams as flow short distances down steep slopes directly into the present Tennessee are not comparable with streams heading in the ridge, but flowing some distance out across the open valley to join the main stream, or its tributary, the Sequatchie. Thus, in the immediate vicinity of the gorge, where the streams enter the main Tennessee while it is still fairly within the limits of the Walden syncline, dissection of the ridge is very marked, as at points west of Brown's Ferry, east of Kelley's Ferry, and along Running Creek just south of the gorge. This local dissection, consequent in part upon the 250 feet of post-Tertiary trenching of the main Tennessee, is wholly in accord with the hypothesis that the Tennessee has held its present course since Cretaceous times.)

In order to account for the diversion of the upper Appalachian independently of this process, which involves such great dissection by obsequent streams, it has been suggested that the diversion may have been accomplished by what has been termed "cavern capture." This process involves a leakage from the Appalachian valley east of the ridge into the Sequatchie valley to the west, whereby a system of caverns was developed in the limestone below the massive sandstone cap of Walden Ridge, resulting in a diversion of the Appalachian River through this underground channel into the Sequatchie River, with the subsequent falling in of the cavern roof. There are several objections to this theory. It is difficult to conceive that the Sequatchie valley could have been lower than the valley of a great river to the east, as is pointed out more fully in a later paragraph, so as to admit of such a leakage as this theory involves. The process would entail

a cavern or series of caverns twenty-five or thirty miles in length, having a beautiful meandering course, developed under a massive cap of hard rock which came down nearly or quite to the level of the valley floors. As Dr. Hayes has pointed out to me, such underground channels would in this case run counter to the trend of geological structures in the region, whereas it is generally true that caverns are developed parallel with such structures. The impossibility of accepting this theory is further evident from the consideration of points to follow. We are therefore forced to the conclusion that the present breach through Walden Ridge was made by the Tennessee itself, it having maintained its present course from a former baseleveling period.

Character of the divide south of Chattanooga.—The Tertiary peneplain on the present divide between the Coosa-Alabama and Tennessee basins, south of Chattanooga, is less than 1,000 feet above sea-level. Those elevations rising to or above the 1,000-foot contour are to be regarded as monadnocks which projected above the peneplain at the close of the Tertiary baseleveling period. Care was taken to verify this statement in the field, in order not only to guard against errors arising from incorrect maps, but particularly to eliminate the effect of possible warping of the peneplain so much as to bring it up to the 1,000-foot level. It was thus found that for a number of miles north and south of the divide those elevations contoured as 1,000 feet or over, as well as a number of elevations not so represented on the map, rose distinctly above the peneplain level, and that the above statement as to the altitude of the peneplain is correct.

Now, if we take the Ringgold topographic sheet and color the areas remaining unreduced at the close of the Tertiary cycle, it brings out very clearly one serious objection to the proposed theory of capture. It will be seen that numerous remnants, some of them over 200 feet in height and of considerable areal extent, were left unreduced on the present divide between the Tennessee and Coosa basins. The supposed former southward course of the Appalachian across this divide must have led between these remnants, because the capture is represented as taking place at the close of the Tertiary. In order to accept the theory of capture, then, we must conceive that a great river, flowing over soft, valley-making rocks, still found itself at the

close of the long period of Tertiary baseleveling, confined for a number of miles in one part of its course (the present divide) by soft rock monadnocks of considerable magnitude to a valley less than two miles in width. This, however, is inconsistent with the accepted theories of valley development. It is thus seen that the features of this present divide are not such as would characterize a region of soft rocks occupied for a long time by the middle course of a great river. On the contrary, the frequent occurrence and large size of the unreduced remnants contrast strongly with the portions of the present Tennessee valley in the same rocks north and south of the gorge, but compare favorably with other divides between the headwaters of small streams, as, for example, that between East Chicamauga and east Armuchee Creeks, on the opposite side of Taylor Ridge, where no large stream is supposed to have ever held its course. When seen in the field, this objection to the supposed former southward course of the Tennessee across this divide is brought out even more strikingly than on the maps; and one is forced to conclude that the river has held its present course for a much greater period of time than since the Tertiary, and that no great Appalachian River could have flowed southward across this divide.

It is possible that an appreciation of this difficulty led Dr. Hayes to place the date of the diversion later than was done in the earlier paper by himself and Mr. Campbell. In the original essay the statement was made: "That the Appalachian drainage was diverted to its present course before this uplift is quite certain, for no channels are cut in the Tertiary peneplain across the Coosa-Tennessee divide" (1894, p. 115). In the later paper Dr. Hayes says:

> The large axial stream in the Appalachian valley continued to flow southward across the present divide for a short time after the uplift, but it was able to cut its channel less than 100 feet in the peneplain before it was diverted to a westward course (1899, p. 55).

It will be seen that this latter interpretation, which regards the present level of the divide as a channel cut below the peneplain instead of a part of the peneplain itself, would mean a reduction of something less than 100 feet in the heights of the monadnocks referred to, and a decrease in their areal extent. But while this provides for a somewhat wider valley for the supposed Appalachian River, it does not

fully satisfy the objection urged, and does involve two other serious difficulties. If we accept a theory of a channel across this divide at the point north of Lafayette, we must account for the fact that small branch streams all over this area have been able to develop low, flat divides of remarkably uniform altitude, and having the same elevation as the channel in question. And, since in nearby areas elevations of 1,000 feet are represented by Dr. Hayes as monadnocks rising above the peneplain, we must either accept the idea of the narrow valley north of Lafayette referred to in the preceding paragraph, or else assume a very restricted local warping of more than 100 feet in four miles. It is also true that no direct evidence of the existence of any channel across the divide has been presented. For these and other reasons that will appear, I am forced to agree with the earlier statement that "no channels are cut in the Tertiary peneplain across the Coosa-Tennessee divide."

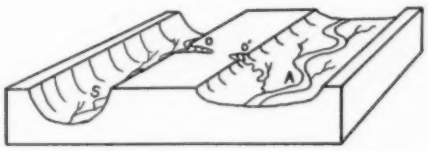

FIG. 9

Insufficient inequality of levels between the two valleys.—In order that one stream, *S* (Fig. 9), may divert another stream, *A*, from its course, it is essential that the stream *S* occupy a level so much lower than its neighbor *A* that even the uppermost headwater portions of the branch *O* which effects the capture shall eventually be able to work at a lower level than that of the stream to be captured. That a small branch of the Sequatchie River, a stream which is itself comparatively small, could work back through a high mountain barrier along a course over 40 miles in length, and still have its headwaters low enough to capture the large Appalachian River, demands that the Sequatchie valley west of the ridge should have been much lower than the Appalachian valley to the east. Several conditions indicate that such a marked inequality of level did not exist between the two valleys at the close of the Tertiary cycle.

On theoretical grounds alone we should be led seriously to question the possibility of such an advantage of position developing

under the conditions preceding the supposed capture. It is difficult to conceive that a small stream like the Sequatchie, having its very beginning less than 70 miles to the northward, and flowing over 300 miles to the sea without receiving the waters of any large stream, could have reduced its upper course to a lower level than the middle course of a neighboring great Appalachian river. It is true that the smaller stream would have had some advantage of more direct outlet to the sea, as the region of the gorge is something over 300 miles from the mouth of the Sequatchie and about 400 miles from the mouth of the Appalachian, as represented on Hayes and Campbell's map of the Tertiary peneplain. It is also possible that there is some difference in the character of the rocks over which the streams were flowing, which was to the advantage of the smaller stream, although both were developed largely on soft rocks. But, after making all due allowance for these advantages, it is still impossible to admit that, whereas the great Appalachian River still had a fall of 3 inches per mile throughout its middle and lower courses, the comparatively small Sequatchie had reduced its gradient almost to zero even in its upper portion, as has been represented.

The fact that the Tertiary peneplain is somewhat lower in the Sequatchie valley than in the valley east of the ridge, while presenting grave difficulties in the way of a satisfactory explanation on the basis of the theory of capture, is wholly in accord with the alternative theory. We should expect the peneplain to be higher on the eastern side of the ridge, for two reasons: it is there farther upstream; and, what is probably of greater importance at this point, the stream in flowing from east to west passes through a mountain barrier which sheds abundant waste into its waters and obstructs its passage with coarse débris, compelling the maintenance of a steeper gradient throughout 25 miles or more; and when it is remembered that nearly or quite to the close of the Tertiary period the mountain served as a sandstone barrier in the path of the stream, it is seen that the base-leveling process must necessarily have gone on at a higher level in the valley in soft rocks east of the ridge. The observed difference in elevation is not greater than we should expect under the conditions referred to, and is not believed to be sufficiently great to account for the proposed capture, even were it possible for this difference to

have been developed under the conditions imposed by the theory of capture.

Hayes and Campbell report the occurrence of the Tertiary river gravels on remnants of the Tertiary peneplain about Chattanooga, 250 feet above the present river, and in the Sequatchie valley, 150 feet above the river. If this difference of 100 feet in the relative elevation of the gravels were correct, it might be advanced as evidence in favor of the theory of capture; for on the basis of the alternative theory we should expect to find the gravels about as high above the river on one side of the ridge as on the other. On the contrary, if these gravels should be found 250 feet above the river in the Sequatchie valley, that in itself would be practically conclusive against the proposed capture, as it would show the former presence of the river at an elevation incompatible with the theory advanced.

North of Shellmound, in the Sequatchie valley, is a series of hills which rise well above the present valley floor. The contour lines show the summits of these hills to be something over 200 feet above the river. The Tertiary gravels, of material that could have been brought from far to the northeast by the Tennessee River alone, are abundantly developed on these hills, completely cloaking the summit in one case. Barometric readings showed that the gravels occur up to 265 feet above the level of the river itself, or about 230 feet above the river floodplain.

Absence of Tertiary gravels south of Chattanooga.—The Tertiary river gravels are abundantly represented about Chattanooga and in that portion of the longitudinal valley to the northward of the city. These gravels occur capping remnants of the Tertiary peneplain and widely distributed over lower levels. Their presence in the valley west of the ridge and southward from the gorge has been also noted. Therefore, if the river flowed southward into the Coosa-Alabama system until the close of the Tertiary cycle, we should find ample evidence of that fact in the distribution along this former southward course of the gravels which are so abundant along the present course of the river. These gravels cannot be confused with any that might be derived from sandstones or conglomerates locally represented, but, as has been pointed out by Hayes and Campbell, must have been brought from far to the eastward. And since these

gravels are so well preserved on the small remnants of the Tertiary peneplain situated near the present river and subjected to extreme erosion, they should show doubly well on the beautifully preserved portions of the peneplain near the present divide south of Chattanooga where post-Tertiary erosion has been at a minimum. On the other hand, if the Tennessee River took its present westward course before the close of the Cretaceous period, and has maintained that course throughout all Tertiary and more recent time, we should not expect to find any such development of the gravels in the valley southward from Chattanooga. Indeed, even if in earlier Cretaceous times the river may have held some course carrying it farther southward in this region (as is possible, perhaps even probable, on the basis of either theory), the most that we could expect to find in the way of gravels would be occasional scattered pebbles having no relation to the Tertiary peneplain, since the erosion of Tertiary time must have swept away all but occasional traces of what may have existed in a former period.

North and south of the divide the valley was examined for a distance of forty miles to ascertain the character of the stream dissection and to discover traces of the Tertiary gravels. About 100 miles of road were traversed, peneplain remnants being visited and beds of streams examined. In all this district not more than a few dozen pebbles were noted, aside from the angular fragments of chert, etc., evidently of local origin. These gravels occurred at scattered intervals, usually only a few at a place, and in or near the beds of streams draining high land areas. A longer and more detailed search would, of course, show other scattered traces of these gravels, but their extreme scarcity cannot be doubted. This remarkable lack of the gravel seems irreconcilable with the theory of capture, but is just what we should expect on the basis of the alternative theory.

On the divide between the Tennessee and Coosa-Alabama basins the Tertiary peneplain developed in this broad valley east of the ridge is very well preserved. As has been pointed out before, this peneplain is not well developed across the entire breadth of the valley, but where it has been so developed it remains very little dissected by subsequent erosion. The conditions are here especially favor-

able for the preservation of the gravels represented elsewhere so abundantly on mere scattered remnants of the peneplain. But not a trace of the gravels could be found over this area, nor on any surface elsewhere south of Chattanooga which could be referred to the Tertiary peneplain. It thus appears that the true Tertiary gravels are wholly absent in the valley southward from Chattanooga —a fact which forces us to the conclusion that this valley was not occupied by the stream which left such abundant evidence of its presence on the Tertiary peneplain elsewhere.

SUMMARY AND CONCLUSIONS

There are many features in the physiography of the Chattanooga district which are of great interest and importance, to which it was impossible to give special attention in the time at the writer's disposal. A detailed discussion of these features will be found in the reports by Dr. Hayes and Mr. Campbell. It may be said in general, however, that it appears that all of these features may be interpreted in accordance with the theory that the Tennessee River has held its present course since near the close of the Cretaceous period. The warping of the peneplains, which was supposed to determine the point of the proposed capture, may doubtless be present; and while it is not believed that such a broad, gentle arching as marks that region could sharply limit a series of divides to a given line representing the axis of the uplift, the presence of such warping is perfectly admissible on the basis of the conditions which are believed to have existed. That the drainage on Walden Ridge north of the gorge is to the eastward, while the drainage south of the gorge is to the westward, seems wholly in accord with what we should expect when the master-stream of the region is east of the ridge in the one case, and west of the ridge in the other. Those streams flowing into the master-stream by the most direct route would have a marked advantage over their neighbors flowing in a longer, more roundabout course, and would in consequence gain control of a large part of the area drained, pushing the divide to the western part of the ridge north of the gorge, and to the eastern part of the ridge south of the gorge. That the drainage in Cretaceous times may have been very different in places from what it is now, and that parts of

this drainage may have persisted far enough into the beginning of the Tertiary cycle to leave traces of its existence on portions of Walden Ridge, is conceivable on the basis of either theory.

In summing up the evidence which has been presented in favor of the theory of a recent westward diversion of the Tennessee from a former southward course, it has been pointed out that while the facts noted in that connection admit of a rational interpretation on the basis of the theory of capture, they are to be explained just as readily and satisfactorily entirely independent of that theory.

On the other hand, there are certain grave objections to the proposed theory of capture, and certain lines of evidence which seem to prove that the Tennessee River has held its present course throughout Tertiary and more recent times. The winding character of the gorge, on the basis of the theory of capture, necessitates a process of diversion so involved and complicated that one is led to seek a more simple explanation for the phenomenon. The conception of meanders inherited from a former baseleveling period offers such an explanation. The character of stream-dissection on the ridge both north and south of the gorge is seen to bear strong evidence against the theory of capture, but is wholly in accord with the alternative theory. The complete breaching of the massive sandstone cap in several places by small streams at a time when larger and more powerful streams had scarcely begun that work, appears incredible. The divide south of Chattanooga is seen to present features distinctly different from what we should expect had a large stream flowed across it until the close of the Tertiary baseleveling period, but well in accord with the features observed on other divides developed by small streams working under similar geological conditions. In order to accept the theory of capture, we must admit that the headwater portion of a comparatively small stream, having, apparently, no marked advantage in regard to its length or the rocks over which it flowed, was able to reduce its valley to a considerably lower level than the middle portion of a great river near by—a thing which does not seem possible. The supposed former difference in relative elevation of the river-brought gravels above the Tennessee in the two valleys—advanced in favor of the capture—is seen not to exist. The

altitude of these gravels noted in the Sequatchie valley strongly negatives the possibility of the proposed capture. The absence of the gravels from the peneplain southward from Chattanooga and the presence of nothing more than occasional scattered pebbles whose distribution indicates their Cretaceous age, completes the evidence that the Tennessee River has persisted in its present course through Walden Ridge for a long period of time, probably since the close of the Cretaceous period at least.

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ADDITIONAL NOTE ON HELICINA OCCULTA

B. SHIMEK
Iowa City, Iowa

Since the publication of the paper on *Helicina occulta*[1] the writer visited the type locality at New Harmony, Ind., from which Say obtained his fossil specimens of this species. Not only did the more or less plant-covered bluff from which Say probably obtained his specimens yield a number of shells, but more numerous specimens were obtained from several large exposures along the roads leading south from New Harmony which have been excavated since Say's time. The species is not as common, however, as in many of the more westerly localities.

Two loesses also occur here, the lower being the characteristic post-Kansan loess, and the upper, a light yellow loess, probably post-Illinoian. Few shells of *Helicina occulta* were found in the upper loess, and they average about 6.5 mm in diameter.

The species is more common in the post-Kansan loess, and the shells from this loess are of special interest because of their large size. In the paper cited (pp. 177–79) the diameter of the largest fossil shells known from the loess is given as 7.25 mm, while that of the largest known recent specimens from the loess-covered region is 7.50 mm.[2] Several of the shells from the post-Kansan loess of New Harmony measure 7.50 mm, and the average is more than 7 mm. Thus the range of variation in the size of the recent shells within the loess-covered territory is fully equaled by that of the fossils, and differences in size cannot, therefore, be accounted for by general climatic conditions. The distribution of the smallest forms of this

[1] *Proceedings of the Davenport Academy of Science*, Vol. IX, pp. 173–80.

[2] The largest authentically reported recent specimens were collected by Walker and Pilsbry on Mount Mitchell, North Carolina, and are reported in the *Proceedings of the Academy of Natural Sciences*, Philadelphia, in May, 1902, on p. 421, as follows: "A few large specimens, diameter 7½ to 8 mm, were found under the dead leaves around the roots of the basswoods and buckeyes." This locality, however, is far outside the loess-covered region.

species, as well as the example of other terrestrial shells such as *Succinea obliqua*, *Polygyra multilineata*, etc., would suggest rather that local variations in the minimum amount of moisture are responsible for the differences in size, the smallest shells occurring in the driest or most exposed places. The average diameter of both recent and fossil forms becomes a little less as we go westward into drier regions, and "depauperation," so far as it exists not only in this, but in other species which occur in the loess, points decidedly toward a dry rather than a cold climate.

Perhaps further emphasis should be placed upon the distribution of both the recent and fossil forms of this species. Reference to the first paper on *Helicina occulta*[1] shows that the northernmost points at which recent specimens of that species were collected are Winona and Stockton, Minn., and De Pere, Wis.; the westernmost point is Eldora, Iowa; the most southerly point is South Pittsburg, near the southern line of Tennessee; while eastward the species extends beyond the mountain to Virginia. The southern limits of distribution lie beyond the border-line of the southernmost drift-sheet, the Kansan, and the eastern limits extend beyond the southeastern border-line of the Wisconsin drift. Northward the species extends locally over the Iowan, and a portion of the Wisconsin drift areas (in Minnesota (?) and Wisconsin), and also over a part of the driftless area in Iowa.

The fossils are more restricted in both their northerly and southerly distribution, but extend farther west, being known from the southwestern part of Howard County, Nebraska.[2] The known northern limit extends from Cuming County, Neb., to Woodbury and Johnson Counties, Iowa, Moline, Ill., and Sullivan County, Ind.[3] The southern limit, so far as is now known definitely, is at Kansas City, Booneville, and St. Louis, Mo.; Gallatin County, Ill.;[4] and Posey County, Ind. Owen also mentions *Helicina*, without specific name,

[1] *Loc. cit.*, pp. 174, 175.

[2] See *American Geologist*, Vol. VII (1891), p. 40.

[3] Reported from the last locality by Collett, *Second Report of the Geological Survey of Indiana* (1871), p. 227.

[4] Reported by Cox, *Geological Survey of Illinois*, Vol. VI (1875), p. 210; *Economic Geology of Illinois*, Vol. III (1882), p. 561.

as occurring in Hickman County, Ky.[1] This is probably *H. orbiculata*, as Dana reports this species from Hickman, Ky., on the authority of Wetherby,[2] though Hickman County is so near the southern limit of fossil *H. occulta* that it may have been the latter species. However, neither conclusion would affect the discussion herein presented.

Since these two species have been frequently confused, the error leading to erroneous references to distribution which would mislead those who are not familiar with the facts in the case, some additional notes on this point are here offered.

Binney's and Aughey's errors have been noted in the previous paper.[3] In 1868 Tryon repeated Binney's error,[4] stating that *H. occulta* is found "fossil and bleached in the post-Tertiary of the western states, Indiana, Ohio, Mississippi, etc." All the authentic records of *Helicina* from Mississippi are those of *H. orbiculata*. Dr. A. Binney reported that species from the loess of Natchez in 1846.[5] In 1854 Wailes reported "*Helix helicina*" from Mississippi, this evidently being intended for *H. orbiculata*. The writer found it very common in the loess of Natchez in 1898,[6] but did not find *H. occulta*. It is safe to say that all specimens of fossil *Helicina* reported from south of Kentucky are *H. orbiculata*, fossils of that species being known only from the loess bluffs along the Mississippi River from Mississippi to Kentucky. Recent specimens of the species may be found from southern Florida to Texas, and northward to Tennessee, and Jasper County, Mo., the latter being the most northerly locality known.[7]

Other errors have resulted from this confusion of species. Thus, in 1875, Cox stated[8] that *Helicina occulta* Say, "has not, I believe, been found living north of Arkansas." The statement applied, at the time, only to *H. orbiculata*. Dr. Snyder's report of *H. orbiculata*[9]

[1] D. D. Owen, *Geological Survey of Kentucky* (1856), p. 18.

[2] *Manual of Geology*, 4th ed. (1895), p. 966.

[3] *Loc. cit.*, p. 176.

[4] *American Journal of Conchology*, Vol. IV, p. 12.

[5] *Proceedings of the Boston Society of Natural History*, Vol. II, p. 130.

[6] See *American Geologist*, Vol. XXX, pp. 279–98.

[7] See *Nautilus*, Vol. VIII (1894), p. 18.

[8] *Geological Survey of Illinois*, Vol. VI (1875), p. 210.

[9] In Leverett, *The Illinois Glacial Lobe*, Monograph No. XXXVIII, U. S. Geological Survey (1899), p. 171.

from Virginia, Ill., is also manifestly an error. The same probably applies to Dr. A. Binney's report of the same species from Ohio.[1]

Neither recent nor fossil *H. orbiculata* extends northward to the border of the Kansan drift, both reaching almost the same latitude, that of the southwestern part of Kentucky. It is, therefore, decidedly a southern species, which has never been found in any condition in colder regions, and it is an abundant fossil in the southern loess. Indeed, the genus *Helicina* is almost wholly tropical, and before the habits and distribution of modern *H. occulta* were understood, the presence of a representative of this genus in the loess was looked upon as evidence that the climate was once *warmer* than at present. In this connection it may be of interest to read Dr. A. Binney's observations on this point, made more than half a century ago in connection with a discussion of the fossils of the Wabash River loess.[2] As the work in which it appears is not easily accessible, the material portion is quoted in full:

> As the genus *Helicina* belongs mostly to inter-tropical regions, and has rarely been met with in a recent state in so high a latitude as that occupied by these fossils, a good deal of importance has been attached to its occurrence here as indicating such a change of climate as has been alluded to. But this supposition creates more difficulties than it obviates, for the numerous species of other genera found in company with the species in question, and which live at this time in the same district in which the fossils are situated, must, according to this view, have also been adapted to a warmer climate than the present, though they do not now exist in southern latitudes, and therefore a very considerable change in their habits must have *since* taken place. Notwithstanding the facility with which the terrestrial mollusks accommodate themselves to the physical influences which act upon them, such a change is not consistent with what we know of their history, and hence the most reasonable conclusion is that the climate in which they lived, from the days when the multitudes which now compose the mass of the fossil beds were in the enjoyment of life upon the surface of the earth, to the present time, has remained essentially the same.

Dr. Binney did not in his day, of course, take into account the intervals between the several loesses, during which it is more than probable that the climate was severe. With this modification his statement concerning the climate is still further borne out by the species under discussion, for it is now known that the habits of *H. occulta* are essen-

[1] *Terrestrial Air-breathing Mollusca of the United States* (1851), Vol. II, p. 353.

[2] *Ibid.*, Gould's ed., Vol. I (1851), pp. 182, 183.

tially the same as those of a number of terrestrial species now inhabiting the same area, and also often associated with this species in the loess. The present writer, long before he had access to Dr. Binney's work, repeatedly called attention[1] to the fact that the climate during the deposition of loess, as indicated by the fossils, was similar to that which prevails in the same region at the present time, and *H. occulta*, in common with a number of other species of terrestrial mollusks, offers strong testimony to this effect. The species does not extend far to the north, either in recent or fossil form, nor was it pushed far south by the ice-sheets following the Kansan. We have direct evidence of its existence only since the Kansan, but even if it occurred previous to the advance of Kansan ice, as it probably did, it still had plenty of room southward in which to persist. From this territory it again spread northward, but was checked by each of the ice-sheets following the Kansan. How far north the species extended during the several intervals preceding the final advance of the Wisconsin ice cannot be determined, as each advancing ice-sheet destroyed all the evidence of their presence, if any existed. That its advance[2] to the more northerly localities in which it lives today was comparatively recent, however, is supported by the fact that it has nowhere been found fossil in these northern localities. Thus, while recent specimens are not uncommon in Winneshiek and Howard Counties, Iowa, the loess of these counties has as yet yielded no fossils of this species.

Helicina occulta is not arctic, nor is it associated in the loess with species which are distinctively arctic. The fact that its range was not greatly extended during the oscillations of the successive glacial advances, and that it remained practically unchanged through all the interglacial loess-forming intervals, indicates a greater lack of

[1] First in the *Proceedings of the Iowa Academy of Sciences* for 1895, Vol. III, p. 85, and subsequently in several papers.

[2] The question might here be raised as to the manner in which such advance could be made. While the writer does not contemplate here the discussion of this subject, he desires to suggest that, among possible agencies, violent storms may be included. The *American Journal of Conchology*, Vol. V (1870), p. 118, contains the statement that "John Ford exhibited specimens of *Gemma gemma* Totten, remarkable for having fallen during a storm which occurred at Chester, Pa., on the afternoon of June 6, 1869." *Gemma gemma* is a small marine bivalve.

plasticity and adaptability than that which is displayed by almost any other terrestrial species. It therefore, supports, better than any other single species, the conclusion that in time past the conditions under which this and other loess species existed were essentially like those under which this species lives today—especially those which pertain to climate and vegetation—and that, therefore, during the deposition of the fossiliferous loess the climate was not glacial.

THE GLACIAL FEATURES OF THE ST. CROIX DALLES REGION[1]

ROLLIN T. CHAMBERLIN
The University of Chicago

Lying partly in Wisconsin, partly in Minnesota, this region has claimed the attention of the surveys of both states and is covered in their reports by general descriptions, in common with the adjacent regions. Because of their clearness and grasp of the salient points, the accounts to be found in Vol. III of the *Geology of Wisconsin* relative to the main movements of the Superior glacier in the northwest section of that state, form an excellent introduction to a detailed study of the St. Croix Dalles quadrangle. The Kewatin glacier, whose drift barely crosses the river into Wisconsin, has fallen to the Minnesota geologists to investigate. The differentiation of the glacial deposits of the last epoch into the red and gray drift, whose upper, oxidized portion is spoken of as the yellow till, appears in the works of Winchell[2] and Upham[3]. More recently a part of the Dalles quadrangle has been subjected to a closer, detailed investigation by Dr. Berkey,[4] who describes, among other aspects of the Pleistocene, the two drifts, the erosion of the St. Croix channel, and the river terraces. In that article the view of the Minnesota geologists, that the ice-sheet of the red drift advanced across the region from the northeast, is entertained.

The topography of northern Wisconsin, in so far as it was molded

[1] My first acquaintance with this region was made as a member of the field class of Dr. W. W. Atwood in July, 1904, at which time the views of Dr. Berkey, and the Minnesota geologists, relative to the formation of the red drift by a movement from the east, and of the gray drift by a movement from the west, and related interpretations, were assumed to be correct, and made the basis of our working hypotheses. At the close of the work, however, some of the interpretations were unsatisfactory. After spending an additional month in further study under a wider range of alternate hypotheses, I have reached the conclusions set forth in this paper.

[2] N. H. Winchell, *Geology of Minnesota*, Vol. I, p. 126.

[3] Warren Upham, *ibid*, Vol. II, pp. 399–425.

[4] C. P. Berkey, *American Geologist*, Vol. XX (1897), pp. 345–83.

during the last glacial epoch, was due to the work of glaciers from the Labrador ice-cap. But over a large part of Minnesota the surface drift dates from an invasion of the Kewatin ice-sheet from the northwest. The Labrador ice arrived first, covering much of Minnesota; subsequently its deposits were buried by the advance from the northwest. The eastern limit of the Kewatin invasion was reached near the St. Croix River, in the vicinity of the Dalles.

The St. Croix Dalles quadrangle comprises those portions of Polk County, Wis., and Chisago County, Minn., which border on the St. Croix River between latitude 45° 15′ and 45° 30′, and longitude 92° 30′ to 92° 45′. The river, with some windings, flows generally south through the western half of the quadrangle. On opposite banks are the centrally located towns of Taylor's Falls and St. Croix Falls, while seven miles downstream is Osceola, Wis. The region as a whole is covered with a thick mantle of drift, which effectually hides the rock formations, except where uncovered by the river, or where an occasional boss of Keweenawan trap protrudes with a *roche moutonnéed* surface.

There are not only two separate drift-sheets represented as surface formations in different parts of the quadrangle, with the likelihood of an older till below, but the two dissimilar drifts both belong to the Late Wisconsin. The Dalles region is peculiar in having the eastern half of the quadrangle glaciated by the Labrador ice-sheet, and the surface of the western part covered by till from the Kewatin sheet. The glacier from the former source was the first to appear as a vigorous sheet, spreading heavy deposits of drift over the entire area. First to come, it was the first to go. It had retired quite beyond this region before the weaker development from the Kewatin gathering ground, spread to the St. Croix River. This ice crossed into Wisconsin less than a mile at St. Croix Falls, though about four miles in the vicinity of Osceola; but it quickly withdrew, leaving in most places only a thin covering of Kewatin drift. To get an idea of the work and relative importance of the two ice-sheets, conceive of the glacier of the red drift, or the Superior (Labrador) glacier, as a vigorous, long-enduring sheet, which produced most of the present topography, and of the glacier of the gray drift, or the Kewatin glacier, as a thin, transient advance of ice, which left as its record only a gray veneering of the red hills.

THE WORK OF THE SUPERIOR GLACIER

Whatever older drift there may be in this region has been so deeply buried under the thick Late Wisconsin deposits that no certain evidence of it was seen. The oldest glacial deposit thus far found is the red drift of the Lake Superior glacier. The first characteristic of this drift to catch the eye is its unusually red color, due to the presence of much ferric oxide. The unaltered till is very red; the stratified deposits from which the water has removed part of the coloring matter, less so. Often the surface layer has been partially leached of its ferruginous compounds, which have concentrated below, leaving the soil a brownish color. Another distinguishing characteristic of this till is that it is prevailingly sandy, and only locally clayey, signifying that the path of the ice advance was over an extensive sandstone and crystalline rock area, and that little limestone or shale was encountered. Of like import is the fact that, while there is the lithological heterogeneity characterizing glacial deposits, the pebbles are confined to a group of rocks chiefly of igneous origin, such as diabase, basalt, serpentine, various porphyries, granite and crystalline schists, together with sandstone. Limestone pebbles are conspicuous by their absence. The basalts predominating, the till may be described as a reddish sandy formation containing chiefly dark-colored igneous pebb es and bowlders. The source of this material is the Lake Superior region, the reddish sands coming from the Lake Superior Potsdam and Keweenawan sandstones, which are similarly tinted. Some of the red coloring-matter was also probably derived from decomposed ferruginous igneous rocks.

The movements and path of this ice-sheet are known from previous investigations to be these: The great ice advance from the Labrador snow-fields in the last Wisconsin epoch separated, west of the Soo, into two principal parts—one developing into the Michigan and Green Bay glaciers, which deepened the pre-existent valleys they entered, and partly formed and partly molded the troughs for the bodies of water which now bear these names; the other, similarly fashioning the Lake Superior basin, pushed on to the southwest, and formed the Superior and Chippewa glaciers. The Superior glacier, emerging from the Duluth finger of the Superior basin, deployed over much of Minnesota, and, spreading on its left flank in a south-

easterly direction across the St. Croix, advanced some distance into Wisconsin.

Topography.—In this region the topography, with the exception of postglacial erosion by the river and a few minor streams, is largely

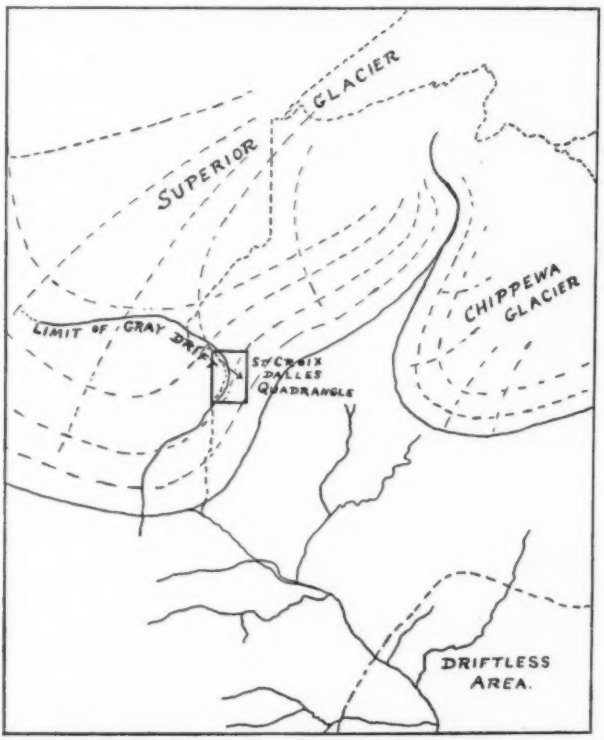

FIG. 1.—Sketch map, showing the general relations of the area of the St. Croix Dalles quadrangle. Data from maps of Wisconsin and Minnesota State Reports.

the work of the ice of the red drift. In the western part the covering of gray till, and the leveling action of the ice which made it, have modified the original red surface somewhat, though not enough to disguise it effectively; in the eastern portion it remains unaltered, so far as later ice advances are concerned. The most prominent features of this topography are three roughly parallel, or concentric

terminal morainic ridges which, running northeast and southwest across the quadrangle, mark successive halts in the glacier's retreat. These may be termed in the order of their ages, the Alden, St. Croix, and Franconia recessional moraines. (See map.) Splendid outwash and pitted-plain topography, especially east of the St. Croix ridge, together with some ground moraine, appear between these morainic belts.

The Alden moraine.—To the oldest of the three terminal moraines which come within this quadrangle, as I interpret them, I have given the name Alden, from the township on the Dalles map in which it occurs. Only a small portion of the big moraine is included in the Dalles sheet, whose southeast corner it crosses. In this neighborhood the axis of the belt apparently runs nearly northeast and southwest, but a short distance beyond the edge of the sheet it must quickly turn nearly due north (as the St. Croix terminal does), for the Alden moraine is found as a wide belt of alternating hummock and kettle, about two miles off the map, northeast of Deer Lake. Just how far east of this belt the outermost terminal moraine of the Superior glacier lies, I am unable to say, though it cannot be a great distance.

While the ice-front oscillated back and forth across this Alden belt, a rough ground-moraine topography was being formed under the body of the glacier to the west. Later, when the ice-edge was at the St. Croix recessional, much of this rough country was covered by outwash. This is particularly true of the northern portion, where only the higher hills of ground moraine have escaped the covering of stratified deposits. But from Sand Lake south, for reasons which will be brought out later, not only the hills, but the great hollows as well, remain. Some of the land appears rather rough for ordinary ground moraine, but it must be borne in mind that this area lies between two adjacent terminal moraines, and that all of the intermediate ground might be broadly included in a comprehensive terminal belt. That the high-hill and lake-basin topography was the type to be seen in the northeast portion of the quadrangle before the outward streamlets began their work, seems probable.

The St. Croix moraine.[1]—After a period of melting faster than the glacier advanced, according to my views, equilibrium was again

[1] Name given by Dr. Berkey, *American Geologist*, Vol. XX (1897), p. 360.

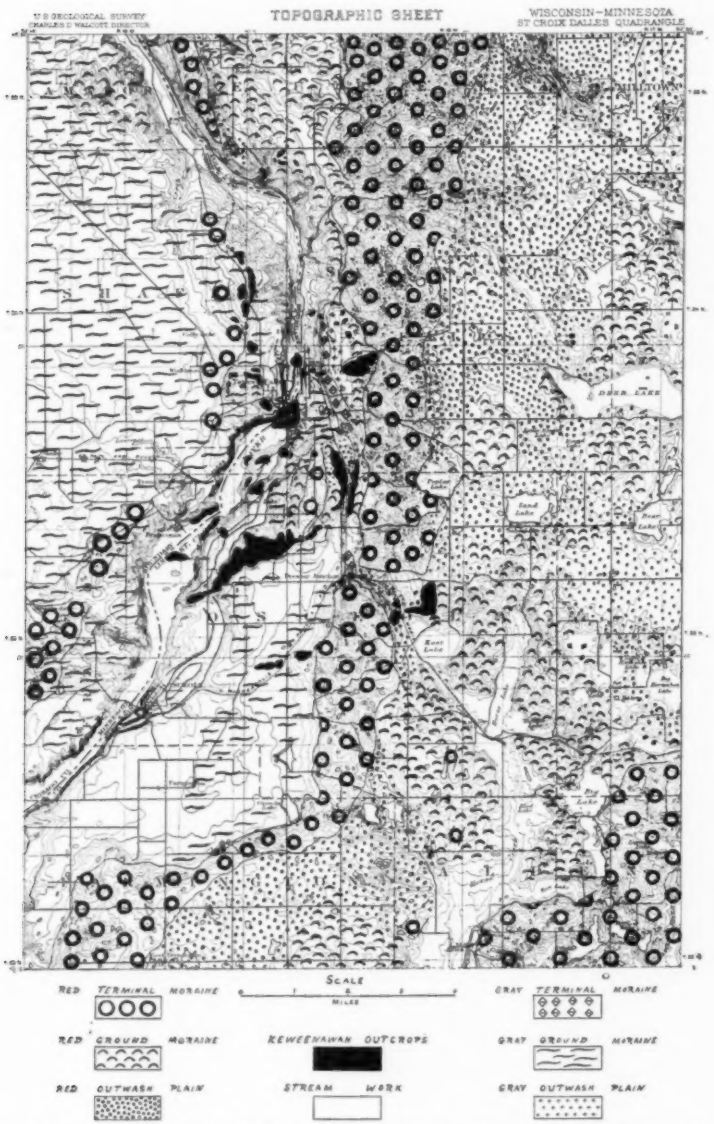

FIG. 2.—The geology of the St. Croix Dalles quadrangle. The Cambrian, which outcrops at points in the bluff of the St. Croix River, is not shown.

roughly established with the ice-front six or seven miles farther west, where the St. Croix moraine was piled up. This belt appears on the quadrangle about midway of the north margin, from which point it runs nearly straight south for ten miles to Dresser Junction, where it is cut in two by a gap. Beyond the gap it continues south for four miles, and then, as a much narrower strip, turns southwest, becoming wider in the extreme southwest part of the quadrangle. (See map.) In width, the belt varies from three miles in the northern portion, to about half a mile in the Township of Farmington. Like the older moraine, its concave side faces west-northwest. It is exceedingly rough and choppy, abounding in hummocks and kettles, knobby ridges, and blind valley depressions, the whole heavily overgrown with small trees and underbrush. The noticeably different aspect of the ridge when approached from the east and from the west is worthy of mention. On its eastern side the moraine merges into a smooth plain dipping gently away from it. There is no steep descent, nor are the moraine hills very much higher than the plain. On the west side, however, a steep declivity along the entire edge of the belt gives it an abrupt, ridge-like appearance. The hills in many places rise 200 feet above the lowland to the west. The significance of this marked difference will be readily understood in connection with the formation of the moraine and its outwash plain toward the east.

The St. Croix outwash plain.—Most of the region between the St. Croix and Alden moraines, with the exception of some hills of ground moraine which stand up above it, and an area near East and Horse Lakes which was never covered by outwash, belongs to the St. Croix outwash plain. With an altitude steadily diminishing to the east and southeast, the plain fades out in the neighborhood of the Alden terminal. East of Long Lake it reaches, and has even buried, some of the lower slopes of this ridge, over six miles from the ice-front at the St. Croix stage. But in general, east of the edge of the map, the outwash development is weak, and the underlying ground-moraine topography becomes more and more pronounced. The smoothness of this gravel plain, its rise near the crest of the moraine, its gentle slope to the eastward, and its mergence into drainage tracts in that direction, furnish the grounds for my inter-

pretation of it as an outwash sheet formed when the glacier stood hard against the western side of the St. Croix moraine.

The surface of the plain is everywhere covered with a fine grayish-brown loam, free from stones, which hides the stratified material. The stratified deposits beneath are of variable thickness, from several scores of feet, as shown by some of the wells, down to two or three feet in road-cuts. While exposures are generally uncommon in the outwash plain and good sections rare, a few of them reveal typical red till underlying the sands and gravels. It is in these that the difference in coloring of the stratified and non-stratified red drift is so noticeable. Along some of the roads in this wide belt, red till appears in some places without any stratified material in sight. These patches are found to be above the level of the surrounding outwash plain on slight eminences which escaped the depositing streamlets. Such isolated hills of considerable size occur northeast of Poplar Lake, and both north and south of Deer Lake. A feature which quickly catches the eye is that on the ground-moraine areas large bowlders are numerous, whereas they are nowhere to be seen on the outwash plain.

One of the pronounced features of the outwash is the pitted-plain development. The pits are of varying dimensions, from depressions in which there are small frog-ponds, up to deep hollows exceeding a mile in length. Many of them contain lakes but many, even of the large ones, do not. The several hundred which are large enough to be represented on the map are pretty evenly distributed throughout the plain, but it is reserved for Eureka Township, in the northeast corner of the quadrangle, to display the most striking pitted-plain spectacle. In this locality there is a splendid series of pits, some of them of great size and as much as 100 feet deep. Their steep sides drop rapidly from the plain in which they are sunk, and the bottoms, instead of being flat, or basin-like, are very hummocky.

The region southeast of the Dresser Junction gap is characterized by a topography not usually seen in the midst of an outwash plain. The question arises: Why do great depressions like the basins of East, Horse, Round, and other similar lakes, exist with ground moraine hills between, when even the hilltops are lower than the level of the outwash plain to the north? Horse Lake is but tw

miles from the St. Croix moraine, and as low as 960 feet, but its basin has escaped filling by outwash material. Less than a mile northeast of the extremity of the lake flat, the outwash plain ends at the 1,140-foot contour. East Lake is still nearer the moraine, but on the east side of the lake, one mile from the terminal, no stratified drift is found, from the 1,100-foot hilltops to below 1,000 feet, where the hill has been modified by the lake when at a higher level than now.

The reason for this considerable area of ground moraine, almost unaffected by the St. Croix outwash, though at a low level, is found in the established drainage lines. Previous to the outwash deposits, a well-developed drainage channel existed from the Dresser Junction neighborhood, past East and Horse Lakes, following what is now the Horse Creek valley, to the Apple River. When the glacier front stood at the St. Croix moraine, the streams from the melting of the near-by ice quickly collected in this course, producing sufficient volume and velocity to prevent extensive aggradation of the channel. Gathered into one course, the rivulets from the immediate neighborhood did not spread out over the country to the east, whose hills and marshes remained unaltered. However, several miles farther east, in the vicinity of the two Horsehoe Lakes, streamlets from the north, which avoided the Horse Creek drainage system, have been able to spread much farther south, where they have partially filled in the low, marshy areas four and five miles from the moraine.

The Dresser Junction gap.—When the ice stood some distance west of the St. Croix moraine, possibly while at the Franconia recessional, perhaps not so far, the high St. Croix morainic ridge blocked the drainage from the melting ice. As a result, the water ponded between the moraine and the ice-sheet until it rose to the lowest point in the barrier ridge, which happened to be at Dresser Junction, whether by chance, or because of the influence of a pre-Wisconsin channel at this point. Upon reaching the proper height, the overflow cut the barrier down rapidly; for, having dropped most of its load in the ponded portion, the water was relatively clear. The Horse Creek channel was still further eroded and the gap lowered nearly to this level. In later times, when the gray ice advanced to Dresser Junction, its outwash went through the gap. The extensive flat east of Osceola

appears to have had its beginning with the ponded waters and outwash from the west.

The Franconia recessional.—The most westerly, and youngest, of the red terminal moraines in the Dalles region, I have termed the Franconia, from the fact that it was first detected on the uplands back of Franconia. It is the most difficult of the three to trace, because most of it has since been rubbed over by the gray ice, which covered what was left with a thin sheet of gray till. As mapped, the chain consists of seven separate links, disconnected by the later ice invasion, but all in a slightly curved strip, whose missing boundaries could easily be drawn. With the exception of the most northerly patch, this moraine lies west of the river in Minnestoa. (See map.) The curved belt is concentric with the two other moraines across the river. In this buried recessional all degrees of terminal topography are displayed, from that which can scarcely be identified, to a strong kettle moraine. Opposite Osceola its great depressions and hummocks have been well preserved; between Taylor's Falls and Franconia station it has been almost entirely obliterated. The veneering of gray drift varies in thickness; on the northernmost strip of this moraine, east of the river, practically no gray till was found, though the presence of limestone pebbles, and also striæ beyond it, proves that this ice once visited that section. Along the railroad tracks, between Taylor's Falls and Franconia, some of the steep banks expose from 20 to 30 feet of gray till, but this is unusual and excessive. The average thickness is perhaps best represented in the strip back of Franconia village, or near Wyckstrom Lake where, in a number of cuts, from 2 to 3 feet of gray drift rests upon the red.

While a strong terminal moraine belt can survive the effects of a subsequent ice advance, and still be recognized by its topography, an outwash plain is much less easily distinguishable under these unfavorable conditions. But by its stratified material it is readily identified. In the road-cuts near Franconia, and from this point south, in the excellent sections revealed by the gullies which are working from the river back into the Minnesota uplands, a thick deposit of stratified sands and gravels is found everywhere to separate the red and gray till-sheets. The lines of contact are sharp. Lithologically, these gravels are the same as the coarse material of

the unaltered red drift, from whose ice-sheet they are unquestionably the outwash. Occurring beneath the gray drift nearly everywhere between the Franconia moraine and the river, they belong to the glacio-fluvial work at the Franconia stage. No limestone pebbles are found *in situ* within these deposits, though much limestone frequently has rattled down, as talus, from the gray drift above, and the gravel has often been cemented into a Pleistocene conglomerate by the calcareous waters from the later till-sheet.

In July, 1904, beds of humus material and clay containing pelecypod and gastropod shells, apparently of land types, were reported to have been found between the red till and the stratified drift above, in one of the gullies south of Franconia. In August these beds could not be found. Evidences of slumping were everywhere, induced by the unusually heavy rains of July; possibly the reported interglacial beds had been buried; perhaps they themselves were earlier slumps partially covered with gravel talus. Elsewhere in the same gully, and in the various tributaries where good exposures of the till and outwash gravels could be examined, the contact was clearly marked without any indication of a soil line. The same conditions obtain in the numerous cuts and sections in the strip between the moraine and the river. Vegetable matter and fossiliferous clay, in place, between the red till and red overwash, would mean that, after the unstratified drift was deposited, the ice retreated west far enough and for a time long enough to permit the growth of vegetation and the immigration of mollusks, and that it again advanced, producing the Franconia moraine and the overwash gravels.

West of the Franconia terminal is a gently rolling ground-moraine topography for several miles beyond the boundaries of the quadrangle. Still farther in this direction, a region of many lakes and some moraine belts was seen from the train; but, since the gray drift becomes thicker toward the west, it was not apparent how much of the topography is to be assigned to the red ice. The main fact is that the red glacier retreated toward Lake Superior before the gray ice invaded the region. How far the red had receded by the time the gray appeared, and where the two ice-sheets met, if they ever did come together, are questions which cannot be answered from a knowledge of the St. Croix region alone. Upham[1] reports a soil line between

[1] *Geology of Minnesota*, Vol. II, p. 414.

the modified drift (red outwash) and the gray above, as found in several places in Chisago County. This would indicate a considerable interval between the two ice-sheets.

The story of the rocks.—The hard ledges of Keweenawan trap-rock in the Dalles region exhibit good stoss sides, which furnish strong evidence of the direction of ice movement. East of the river, and especially east of the gray terminal moraine, the planed sides are almost invariably the west or northwest slopes of the ledges, the few exceptions being clearly local accidents. These may be called the red stoss sides; they occur also on the west side of the river, but here the complication of the Kewatin ice is added. Knobs and tails produced from the resisting amygdules in the diabase agree with the story of the stoss sides. Striæ have not been well preserved on these rocks, which in general have weathered sufficiently to destroy the scratches. By looking over a large number of ledges, however, plenty of records can be obtained. The location, direction, and significance of these can best be understood from the striæ map. While there is considerable variation, owing to the fact that they were made at no great distance from the fluctuating edge of the ice, they tell a consistent tale. The striæ are in three sets.

1. The earliest set of scratches discovered affect only a few outcrops above the bend in the river, four and a half miles due north of Taylor's Falls. In a gully whose stream has cut deeply into the drift and laid bare the Keweenawan, striæ reading S. 11° E.[1] and S. 13° E. were found, accompanied by a more marked set running S. 40° E. Half a mile northeast, the hillside ledges bear striæ S. 8° E., S. 11° E., and S. 15° E. As shown on the map, these were probably made when the ice covered the entire quadrangle and was making its terminal moraine at a considerable distance away. The set of striæ next to be described, S. 40° E., are better represented on these rocks, but those of the latest, or third, group are absent, suggesting that the ledges became covered by drift and were protected during the St. Croix terminal stage. This protection may explain the presence of the old striæ which are not found in less favored places. The weak ice of the gray drift, however, has left a still later set of marks

[1] The directions of striæ are all corrected for magnetic variation.

on the hillside ledges, though those in the ravine which were buried, escaped.

2. The second set of striæ formed by the red ice trend about S. 40° E., with some S. 45° E., and even S. 49° E. These striæ are

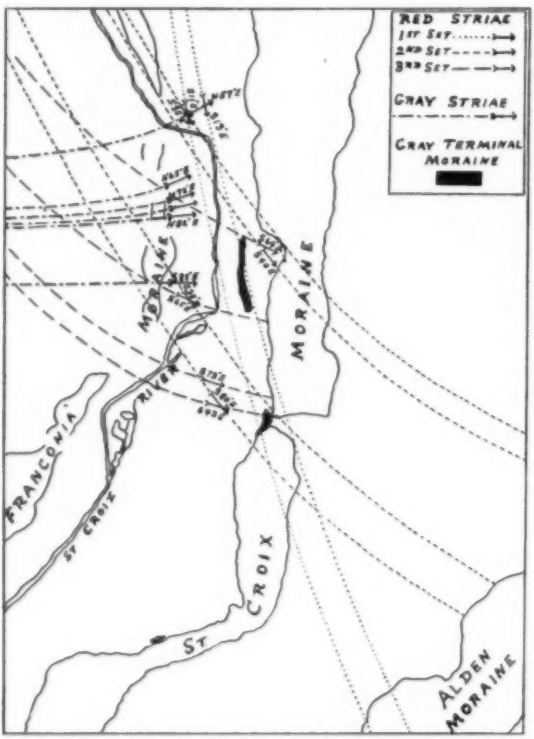

FIG. 3.—Map showing the glacial striæ of the St. Croix Dalles quadrangle

interpreted as the work of the ice-sheet which had its front at the Alden moraine. This set is the most persistent in the region, suggesting vigorous ice-work at this time.

3. The third, and most recent, group of striæ vary from S. 63° E. to S. 80° E., and are thought to have been engraved while the St. Croix moraine was being formed. A comparison of the three sets shows that the first possessed most nearly the direction of main move-

ment; the second, formed as the lateral edge of the ice-lobe came nearer to the rocks in question, deviate about 28° more to the east; while the last, produced near the edge of the ice, trend 30° more to the east. A progressive turning toward the border of the lobe is thus shown. This is in accordance with the law of ice-flow in broad, flat lobes. The general direction of movement of the Lake Superior lobe was southwesterly, but on this, the left flank, its advance was southeasterly toward the ice-edge. The dotted lines on the striæ map are attempts to show this.

Bowlder trains are not of great service as indications of the direction of ice advance in this region, as they are poorly developed. In the lee of only one prominent outcrop—a mile and a half east of Dresser Junction—are the fragments of diabase conspicuous. There bowlders occur in great numbers on the east side of the rock hill.

WORK OF THE KEWATIN GLACIER

Some time after the Superior glacier had withdrawn, the Kewatin sheet, coming down the Red River valley, advanced from the west to the middle of the Dalles quadrangle, spreading its drift over the previous red deposits. This younger drift is strikingly different from the older in several particulars. Its color is a grayish buff, somewhat like that of the drift of southern Wisconsin, though lacking the brownish ferruginous tints. Frequently the surface layer which has been leached exhibits a more yellowish or brownish shade than the unaltered till, due to the oxidation of the iron compounds. While the red drift is sandy, the gray is clayey; the former, as previously noted, contains neither limestone nor shale, both of which abound in the latter. Since much of the western drift is the product of limestone ground up, it follows that it is highly calcareous, except in the upper foot or two where leaching has occurred. The red drift is non-calcareous. Part of the limestone, and most of the dark gray shale which is so characteristic, were probably derived from the Cretaceous strata of western Minnesota and the Red River valley. However, a few Trenton fossils found in the glacial pebbles prove that the Cretaceous series was not the source of at least a part of the limestone in the gray drift.

Gray drift covers all the territory in the quadrangle west of the river, with the exception of some small patches of red drift over which

the western ice crept, but either did not leave any débris, or so little that it has since been removed. In Wisconsin it occurs largely in patches, partly because little or no drift was left in some localities, and partly because of stream erosion. East of Osceola this glacier actually reached the St. Croix moraine; from the north of the map to within three miles of St. Croix Falls no gray drift was found on the east side of the river, though striæ interpreted as belonging to the gray ice, and a few limestone pebbles, indicate that the Kewatin glacier visited these parts. As this region was covered only by the extreme edge of the Minnesota glacier, which seems to have been thin, and not to have remained here long, it did not effect a great change in the topography. Some of the hills of red drift were worn down, and many of the depressions filled, but the covering of gray drift is too scanty to mask entirely the old red topography.

The gray terminal moraine.—While the red terminal moraines in this region are all of the recessional type, though large and prominent, the gray moraine is a limiting terminal marking the extreme extension of the sheet, but it is the weakest and most obscure of all. So far as my knowledge goes, the gray terminal first appears at the north within the quadrangle about half a mile east of the river, and a mile north of St. Croix Falls, where it is very indistinct. North of this, on account of the scarcity of gray drift, it has not been recognized. From this point it runs slightly east of south for two miles, becoming a more pronounced ridge; but it cannot be traced beyond the great pit near the railroad tracks, one mile southeast of St. Croix Falls station. From the pit the boundary of the gray till-sheet swings sharply to the west, and then southwest along the slopes of a high veneered rock hill, until it is lost amid Keweenawan ledges, two and a half miles south of Taylor's Falls. Farther south, however, at Dresser Junction, there is a hummocky ridge, though scarcely more than half a mile long, piled up across the front of the great gap in the St. Croix moraine. This is the best-developed portion of the gray moraine. Considering the position of this strip, and the direction of the ridge running from St. Croix Falls south to the great pit, it appears a plausible view that the ice-front at its maximum point stood along a line connecting these morainic strips, approximately where the railroad is today. However, no gray drift was found on the upper part of

the hill to the west, which must have been overridden by the ice according to this view, nor has any direct evidence appeared in support of this idea. A further study will be necessary to establish this portion of the border line. South of Dresser Junction the terminal moraine was discovered only in a single isolated spot, three miles southeast of Osceola, where, as is strikingly shown in a road-cut, the ice punched against the red St. Croix terminal, leaving the red and gray till in a dovetail contact. That the limit of the gray ice south of Dresser Junction was the western edge of the St. Croix ridge seems probable.

From so transient an ice advance an outwash plain would not necessarily be expected. In but one place, the Dresser Junction gap, where drainage was concentrated, is gray outwash material seen in any quantity. In the gap not far from the Kewatin moraine at least 10 feet of limestone gravel rests upon the older stratified deposits of the Superior glacier.

The Minnesota upland, except in the belt of the buried Franconia moraine, and at a few points where hills of red drift protrude, in the northwest corner of the quadrangle, is surfaced by a gently rolling ground moraine with abundant marshes and undrained areas. The thickness of this drift sheet is variable; on the hillside, a quarter of a mile west of the picnic grounds in Taylor's Falls, the older red drift appears at the surface in an isolated spot; at the picnic grounds, and also in some of the cuts along the railroad to Franconia station, between 25 and 30 feet of gray till are exposed. As previously stated, 2 or 3 feet is about the mean depth of gray material on the Franconia moraine. The thick sections of gray drift which so greatly exceed the average all occur near the river, suggesting a pre-Kewatin valley or depression favorable to greater accumulation of débris. West of this strip of heavy gray drift along the river—between Taylor's Falls and Franconia—the buried red terminal moraine has been nearly obliterated.

Work upon the rocks.—Instead of the northwest sides of the Keweenawan ledges being planed, as is the case east of the gray terminal, the outcrops west of the river are rounded and polished on the west or southwest slopes. In many cases the work of the red ice is still visible, but the southwest stoss sides, fashioned later, are the more

pronounced. These, with the steep drop-off faces on the east and northeast sides, give the general direction of movement, but for more exact data recourse must be had to the striæ. On the hill west of Taylor's Falls the prevailing striæ read in the neighborhood of S. 88° E., showing that the ice moved nearly due east here. In Senator Deedon's yard, a mile and three-quarters to the north, they trend N. 82° E. Farther north, on the opposite side of the road, the following were recorded in order about a quarter of a mile apart: N. 73° E., N. 72° E., and N. 65° E. Across the river, two miles farther north-northeast, scratches were found reading N. 57° E. These varied, but progressively changing, directions put together on the map, show very prettily how the ice of the gray drift spread out near its outer border until, in places it advanced nearly due northeast. On some of the less exposed portions of the *roches* striæ of the Superior ice are still to be seen.

POSTGLACIAL PHENOMENA

Since the Kewatin ice-sheet retreated, the region has undergone some interesting changes, due to erosive action, chiefly that of the St. Croix River. As to what may have been its preglacial course, this region offers little in the nature of a clue. There may have been a preglacial channel past Dresser Junction, and along Horse Creek valley to the Apple River, which lower down empties into the present St. Croix. While the cut between the diabase hills, one and a half miles north of Dresser Junction, was very likely a sluice-way for waters from the melting red ice farther north, to the ponded area, it does not appear to be low enough to form part of a river course before the area just north of it was built up by the thick deposits of drift.

During the early stages of the river's postglacial history, when great floods of water descended the St. Croix from Lake Duluth, much of the flat land east and south of Osceola was temporarily covered, and the already nearly flat area appears to have been still further leveled by sedimentation. Later the river retired to a more definite course which soon deepened. Since the first well-marked course was formed, the stream between Taylor's Falls and Osceola where the most Keweenawan trap-rock was encountered, has migrated westward down the slopes of hard diabase, and cut away the less resistant sandstone and shale. The slopes on the Wisconsin side, opposite

Franconia station for instance, are comparatively gentle, but the Minnesota bank is a steep cliff of Cambrian sedimentaries. A well-developed channel, nearly parallel to the present course and about one mile east of it, can be followed from the bend in the river at the interstate park in Taylor's Falls to Osceola, where it joins the St. Croix today just below Eagle Point. It is not difficult to find the points at which this course was abandoned in the migratory process —first two miles north-northeast of Osceola at a barrier of Keweenawan, next two and a half miles farther upstream at a similar obstacle, again at Thaxter Lake, and lastly at the elbow near Taylor's Falls, where, finding a deep rock fissure, running northeast and southwest, more in line with the new course of the stream below, the opportunity was taken to readjust itself. Some readjustment is evident also above the Dalles in the immediate vicinity of the town of Taylor's Falls.

Terraces.—Objections based chiefly upon the depth of the gorge at the Dalles, and an assumed slowness of erosion through the compact igneous rock, have been raised against considering the canyon to be the work of the St. Croix since the glacial epoch. By Dr. Berkey it has been referred to postglacial erosion. That this is so is evident from a number of considerations. While the river occupied the earlier channel just described, which was long after the ice withdrew, it was cutting the rock barrier of the Dalles at 850 feet, more than 150 feet above the stream-level at this point today. The portion of the Dalles below the bend is still younger. But perhaps the most conclusive and neatest bit of evidence is that furnished by the terraces.

Well-defined alluvial terraces line both banks of the St. Croix above the Dalles, though there are none corresponding to them below the bend in the river, and most of them gradually disappear a few miles upstream. On the Wisconsin side the best benches are at 725 feet, 780 feet, and 810 feet levels; while in Minnesota the most prominent are at 750 feet and 920 feet. There are some correspondencies between the two banks, but, in general, where there are extensive flats on one side, the stream has swept away those opposite. The 750 and 920-foot terraces have small tallying benches across in Wisconsin; but, the 725 and 810-foot flats are not to be found in Taylor's

Falls. Other terraces occur at 880 feet in Taylor's Falls, and 875 feet at its highest point in St. Croix Falls.

The significant feature of these terraces is that none of them is continued below the Dalles. The highest, and that at 880 feet, end against the Keweenawan barrier near the Taylor's Falls schoolhouse; the 750-foot flat, upon which most of the town is built, terminates with the trap-rock in the interstate park; the 875 and 810-foot flats disappear less abruptly on the wooded river banks not far from the diabase ledges; the lowest bench is stopped at the rocks close to the toll bridge. The hard trap-rock at the Dalles acted as a barrier, while the stream above formed a flood-plain. As soon as the falls which developed from the more rapid cutting below the barrier, cut a stope through the barrier and reached the drift above, a trench was quickly cut in the alluvial plain, producing a terrace. At a later time, when the stream-level to the south had lowered sufficiently, falls again developed and produced another terrace; and so on. The pronounced 780-foot terrace, instead of extending upstream from the Dalles, starts with the narrows at the present falls, nearly a mile farther north, where another, but much lower, barrier checked the stream's progress. Falls were therefore here at the time of the formation of that terrace, and with the same reasoning it is safe to predict that the next terrace to appear will be just above the present falls.

The highest of the terraces, at 920 feet, represents approximately the original level of the drift at this point, showing that soon after drainage adopted this course, the igneous rock was encountered, and the stoping process begun; the younger benches, lower upon the slopes of the trench, mark the stages or repetitions of this method of rock erosion with alternate filling and cutting upstream. These post-glacial terraces, intimately associated with, and dependent upon, the receding falls, indicate that the cutting of the deep, but short, gorge in the Keweenawan has all been accomplished by the St. Croix since the retreat of the last ice-sheet.

A FOSSIL STARFISH FROM THE CRETACEOUS OF WYOMING

STUART WELLER
The University of Chicago

A specimen of a fossil starfish has recently been presented to the Walker Museum of the University of Chicago, by Mr. N. H. Brown, of Lander, Wyo. The specimen is preserved in a fine-grained, light yellow sandstone from near the summit of the Upper Cretaceous which may be referred to the Fox Hills formation. Though all the characters desirable for the classification of the specimen are not perfectly preserved, yet there is justification in the description of such a specimen because of the extreme rarity of such fossils in the Cretaceous faunas of America, and because it is probably the best specimen of a Cretaceous fossil starfish yet found in America; at least no specimen so nearly complete has been mentioned in the literature.

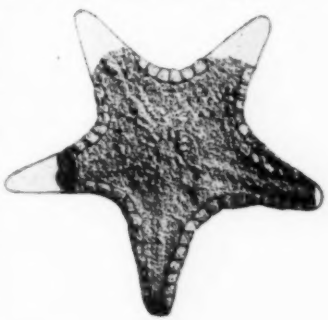

FIG. 1.

The specimen is apparently exposed from its dorsal side, but, apart from the large marginal plates, all the plates of this surface have been destroyed. The impressions of the ambulacral furrows of the ventral surface are exposed by the weathering away of the dorsal surface, and appear as rounded, slightly elevated ridges extending from the arm tips to the center of the disk; but the characters of the ambulacra are not sufficiently well preserved to be accurately determined.

The presence of highly developed marginal plates upon the specimen mark it at once as a member of the order *Phanerozonia*, and it may be placed, without serious question, in the family *Pentagonasteridae*. The reference of the specimen to its proper genus

is less satisfactory, but it seems to agree more closely with *Pentagonaster* than with any other, although the interradial arcs are somewhat deeper than is usual in that genus. In the recent species *P. arcuatus* Sladen,[1] however, these arcs are nearly as deep as in the fossil specimen, the proportion between the minor and major radii being 1 to 1.93, while in the fossil specimen it is 1 to 2.08.

The specimen also more or less closely resembles, in the characters which are preserved, some of the recent species of *Gnathaster*, a genus also belonging to the family *Pentagonasteridae*, in which the interradial arcs are often much deeper than in *Pentagonaster*, in *G. elongatus* Sladen,[2] the proportion of the minor to the major radii being 1 to 3.5. This genus, however, is usually characterized by the presence of an odd interradial marginal plate—a character not clearly shown in the fossil specimen. In one of the interrays such a plate seems to be present, but in the others not. For the present, therefore, the specimen may be referred to the genus *Pentagonaster*.

Pentagonaster browni *n. sp.*

(Fig. 1)

Description: Stellato-pentagonal in outline, major radius 24^{mm}, minor radius 11.5^{mm}. Disk large, apparently flat. Interradial arcs broadly rounded, the rays elongate for the genus, rounded at their extremities. Marginal plates large, about sixteen occupying each interradial arc from tip to tip of adjacent rays, the character of their ornamentation not preserved.

Horizon and locality: Fox Hills sandstone, S. E. ¼, Sec. 16, T. 32, R. 99, near Lander, Wyo.

Type specimen: Paleontological Collection, Walker Museum, No. 10725.

[1] *Challenger Reports*, Zoölogy, XXX, p. 277, Plate 52, Figs. 1, 2.

[2] *Ibid.*, p. 288, Plate 48, Figs. 1, 2.

THE SO-CALLED ALKALI SPOTS OF THE YOUNGER DRIFT-SHEETS

O. W. WILLCOX
Fort Hancock, N. J.

The surface of cultivated fields on the younger sheets of glacial drift in Iowa, Wisconsin, Illinois, and Indiana is frequently marked by patches of a white efflorescence which is distinctly hostile to many cultivated plants, particularly corn. These patches have received the name of "alkali spots" from the farmers of the region, to whom they are a source of perplexity and loss.

Genetically, these "alkali spots" are invariably connected with the small sloughs or lakelets which characterize the extreme topographic youth of drift-sheets. As is well known, the surface of the Wisconsin drift is pitted with countless thousands of these small bodies of water; the Iowan drift bears them in notably smaller proportion, a circumstance in harmony with the more advanced development of the natural drainage of this drift-sheet. In their undrained condition these basins are a hindrance to agricultural operations, although in general the water may readily be removed by drainage; this is being done on an enormous scale in the states mentioned. In a very large number of cases, however, the farmer, after doing away with the standing water, finds the reclaimed land affected by the harmful efflorescence mentioned above.

Analysis shows the efflorescence to consist of small amounts of sodium chloride and much larger amounts of the carbonates and sulphates of magnesium and calcium; magnesium sulphate is a leading constituent. Sodium carbonate is absent; the efflorescence lacks therefore the character of a true alkali, and the soil infested with it is not an alkali soil, as this term is understood in the semi-arid West. The hostility of the soil of the "alkali spots" to corn is due to the presence of excessive amounts of magnesium salts in the soil moisture.

The *raison d'être* of the efflorescence is not far to seek. It will be

borne in mind that many of the innumerable sloughs of the younger drift-sheets occupy the lowest points of depressions without outlet. These depressions constitute isolated basins having an area varying from two or three up to as many hundreds of acres in extent. The floor of these basins consists of the finely pulverized rock-flour characteristic of the ground moraine. Owing to its fineness, the material of the till is in the most favorable condition to be attacked by the agencies of weathering. The alkaline-earth carbonates are attacked and rendered soluble by the carbon dioxide of the air; the sulphur in the pyritiferous minerals of the till is oxidized and converted into sulphuric acid, which ultimately appears in the form of its calcium and magnesium salts. Doubtless a certain proportion of the material dissolved out of the till enters the general underground circulation, but a large part simply collects in the water which has found its way to the lowest part of the basin and has there been concentrated by evaporation. Since the final retreat of the ice, this process of concentration has in many cases brought the percentage of dissolved matter up to a figure quite beyond that which is usual for surface water. This is especially true of small ponds which receive the drainage of large areas; but even those located in small basins frequently contain appreciable amounts of salts, as is apparent from the white residue left on their floors when they dry up in summer. Many of the lakelets of the drift are, on a small scale, embryo salt lakes, in which magnesium sulphate instead of sodium chloride is the principal dissolved substance.

The earth in their vicinity is consequently saturated with water carrying a notable amount of saline matter, chiefly soluble salts of magnesium. When the farmer tiles out the basin, the excess of water is drawn off through the drains. Much of the dissolved magnesium is thus removed, but not all, for no drain will at once remove all of the water; even the percolation of the rain water of several successive seasons is frequently insufficient to wash out all of the deleterious salts.[1] Although these

[1] This will be understood by every student of chemistry who has had occasion to wash a dense precipitate to free it from a soluble salt. The obstinate retention of certain salts freely soluble in water by a finely divided solid is not always purely mechanical. The phenomena of adsorption (*ad*sorption is different from *ab*sorption), of which chemists have only recently begun to take account, come largely into play.

salts are slow to find their way out of the soil through the drains, capillary flow during dry weather readily brings them to the surface, where evaporation raises the percentage of magnesium in the soil moisture in the zone of root-growth beyond the point of toleration by the plants; continued evaporation of the surface moisture produces the efflorescence. If the floor of the slough was originally somewhat peaty, and therefore porous, the efflorescence is fairly evenly distributed over the area formerly occupied by the water; but if, as is more usually the case, the slough has been silted up with fine material, the efflorescence appears in a zone corresponding to its former margin. It is the occurrence of this annular area of barren ground in an otherwise productive field which mystifies the farmer and the agricultural writers.

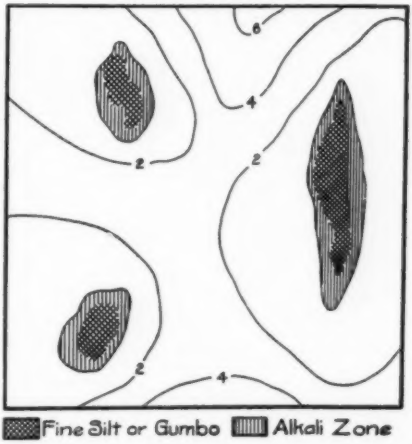

FIG. 1.—Group of small annular "alkali spots" on the Story County Poor Farm, Iowa. (Horizontal scale: 1 inch = 200 feet.)

The occurence of this annular zone of poisonous soil is accounted for on the following considerations: The surface water which finds its way into the slough carries with it both fine and coarse material; the particles of the grade of sand are deposited first, while the silt is distributed farther from the border. The soil and subsoil of the margin are consequently more open-textured than the soil of the interior; hence there is a predominant flow of capillary moisture toward the porous margin, where evaporation renders conspicuous both the efflorescence, and the poisonous condition of which it is the sign.

The essential features of typical "alkali spots" are shown in the accompanying figures.

Adsorption is undoubtedly a considerable factor in geological chemistry, and should receive greater attention from soil investigators.

It is a matter worthy of remark that the immediate surface of the Iowan drift-sheet seems to be much poorer in soluble sulphates than is the case with the Wisconsin. The Iowan has its "alkali spots," to be sure, but their occurrence is due to the preservation of favoring topographic conditions. Where natural drainage has long been established, as in the vicinity of the master-streams, the proportion of soluble sulphates in soils of the Iowan drift is quite normal. It appears to be otherwise with the Wisconsin drift, even in the broken area adjacent to the streams which flow across the tip of the Des Moines lobe south of the Gary moraine; in this region is to be found that part of the Wisconsin drift which, in Iowa at least, has been longest exposed to weathering, since it was the first to be left bare by the retreating ice. Close examination of hillside surfaces in this area after several days of fine weather often reveals the presence of an efflorescence similar in appearance to that found in the "alkali spots;" the presence of soluble sulphates is easily shown by scraping about twenty grams of earth from the surface, extracting with pure water and adding a solution of barium chloride, whereupon a copious precipitate of barium sulphate will be obtained. This appears to be a point of difference between the surfaces of the two drift-sheets.

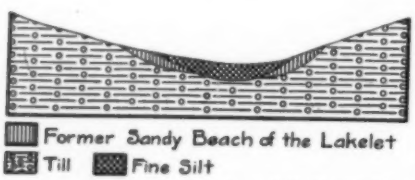

FIG. 2.—Section through an "alkali spot."

It will be recalled that in estimating time ratios within the glacial epoch much weight has been laid upon the obvious differences in the present condition of the upper zones of the various drift-sheets. The absence of lime, the decay of the felspars, the complete oxidation of the iron content so unmistakably patent in the ferretto of the Kansan clearly stamp this till as of greater age than that made by later ice-sheets. No such obvious differences set off the later tills one from the other. The difference between the surface zones of the Iowan and Wisconsin tills in regard to lime content is not particularly noticeable, and the same may be said of the degree of oxidation of the iron in these tills; the granite bowlders of the Wisconsin are not noticeably fresher in appearance than those of the Iowan. The chemical criteria

heretofore in use are apparently not sufficiently delicate to differentiate such recent glacial deposits.

The writer's personal observations are perhaps much too limited to warrant the assertion that a criterion of the required delicacy has been obtained, but there will be no harm in expressing the opinion that more extended observations will probably confirm the preliminary indications. There are abundant reasons for assuming *a priori* that in the earliest stage of the after history of a drift-sheet it will be characterized by a noticeable amount of sulphates and that these will begin to disappear long before any appreciable diminution of calcium carbonate or decomposition of ferro-magnesium minerals have occurred—granted, of course, that the drift contains pyritiferous minerals, which in fact is always the case. Pyrite is peculiarly susceptible to the action of moist oxygen and its conversion into ferrous sulphate and free sulphuric acid follows its exposure to the dissolved oxygen of the ground water. Considering the relatively small amounts of pyrite and sulphates in the drift as compared with calcium carbonate, the great excess of atmospheric oxygen over atmospheric carbon dioxide, and the great solubility of the sulphates as compared with the solubility of calcium bicarbonate, it is quite natural to expect that the surface of the till will be desulphurized much sooner than it will be decarbonated.

PERIDOTITE DIKES NEAR ITHACA, N. Y.

GEORGE C. MATSON
Chicago

The country rock at Ithaca consists of Upper Devonian shales and sandstones. The rocks are traversed by two series of well-marked joint planes. One series extends nearly north and south; the other series, east and west. Both series are at right angles to the bedding planes. In general, the joints are more abundant in the shales than in the sandstones.

Many dikes have been discovered in the north-south joint planes, but none have been found in the east-west joint planes. This fact may be accounted for in two ways. The streams, which usually flow either east or west, cross many more north-south than east-west joint planes. Therefore the dikes in the former are more likely to be exposed than those in the latter. However, as the dikes were probably intruded while the rocks were being folded, it seems more probable that the east-west joint planes, which are roughly parallel to the folds, were kept closed by compression during the period of intrusion.

Location and size of the dikes.—The existence of a few dikes near Ithaca has long been known. Professor J. F. Kemp[1] speaks of the three dikes in Cascadilla Creek near the bridge at the entrance to the Cornell campus, and he also mentions the one in Six-Mile Creek above Green Tree Falls. The dike just above the upper bridge across Cascadilla Creek measures about 3 feet. It outcrops on the south side of the gorge; on the opposite side the gorge wall is covered with débris. The other two dikes are each about 2 inches wide. They show on the south wall of the gorge between the upper and lower bridges.

In his *Geology of the Third District of New York*, Vanuxem[2]

[1] J. F. Kemp, "Peridotite Dikes in the Portage Sandstones Near Ithaca, N. Y.," *American Journal of Science*, 3d Ser., Vol. XLII (1891), pp. 410–12.

[2] Vanuxem, *Geology of the Third District of New York* (1842), p. 169.

speaks of four dikes in a gorge near Ludlowville. This gorge is the first one south of the road running east from the village. Two of the dikes referred to by Vanuxem are located near an outcrop of the Tully limestone; the other two are farther upstream, above a high fall over the Genesee shale. The two dikes near the outcrop of Tully limestone, together with a third located near the base of the fall mentioned above, are each about an inch wide.

Above the high fall, instead of two dikes there are four, all showing on the south wall of the gorge. Three of these have been faulted; the fourth does not reach up to the fault plane. The amount of the displacement is about 2 feet. The largest dike is 7 inches wide in its widest part; the others are all small, varying from 1 to 2 inches. There is much branching, and it is doubtful whether more than one of them reaches the top of the gorge wall. Farther upstream is another fall. Above this fall are several small dikes. These are all less than 2 inches wide and appear only on the south side of the stream.

In the gorge just south of the one above mentioned there are five dikes, ranging from ½ inch to 5 inches in width. These dikes may be merely outcrops of some of those which appear in the other gorge; but unfortunately the intervening space is covered with glacial drift, so that the continuity cannot be established.

Just below Taghanic Falls, five small dikes, all less than 4 inches wide, appear on the south wall of the gorge. At least one of them reaches the top of the cliff. A thrust along a bedding plane has displaced these dikes about 20 inches. There is much branching, which often includes fragments of shale thicker than the dikes themselves. On the north wall of the gorge only three dikes were found. Farther upstream, about 100 yards above where the wagon-road crosses, there is a dike about 2 inches wide.

In Glenwood Creek, above the railroad, a dike 7½ feet wide outcrops in the bed of the stream. About 3 feet of the center of this dike weathers like ordinary peridotite; the remainder takes on a schistose appearance when weathered. This peculiar weathering is due to the presence of many vertical cracks along which disintegration progresses rapidly.

Besides the dike in Six-Mile Creek which was mentioned by

J. F. Kemp,[1] there are four others. Two are just below the old pumping-station, and two are about one-quarter of a mile farther upstream. The two near the pumping-station measure 4 and 9 inches respectively; the two above the pumping-station, 3 and 8 inches.

In a quarry at the south end of Hazen Street in the city of Ithaca there are three dikes, ranging from 2 to 6 inches in width. The possibility of these dikes being connected with those near the pumping-station in Six-Mile Creek, and also with some of those in Cascadilla Creek, should not be overlooked. However, direct proof is wanting, and only the fact that they are all in a line nearly parallel with the direction of the joint planes can be cited as supporting the hypothesis that they are connected.

The rocks penetrated by the dikes at Ludlowville, Taghanic, and Glenwood are Genesee shales and Portage shales and sandstones. The dikes in the immediate vicinity of Ithaca penetrate rocks belonging to the Ithaca Group.

Megascopic appearance of the rocks.—The rock is porphyritic, with a dense black aphanitic groundmass, containing phenocrysts of reddish-brown mica and black fibrous masses having the structure of serpentine. The mica is usually in small glistening scales, with an occasional crystal which has a diameter of one-half inch or more. In some cases crystals of olivine may be seen. With a hand-lens, grains of a black metallic mineral (magnetite) are occasionally found. The phenocrysts of serpentine often cover the surface of the weathered rock as black protuberances, sometimes as much as one inch in diameter. These resemble pebbles, but are soft, and when broken, show their fibrous structure.

As the dikes weather they lose their dark color and become a light greenish-gray. On the surface are many mica scales which have faded to a light brown. Further weathering produces a yellow incoherent clay, containing many scales of light brown mica.

Microscopic description of the rock.—Two well-defined phases of the rock are noticeable: (1) porphyritic, (2) non-porphyritic. The porphyritic peridotite contains abundant phenocrysts of olivine, with a subordinate amount of biotite. The olivine phenocrysts are usually

[1] *Loc. cit.*

altered to serpentine and a carbonate. None of the phenocrysts contain inclusions of magnetite, ilmenite, or perofskite, except such fine grains of magnetite as commonly result from the alteration of the olivine. The groundmass consists chiefly of serpentine with some mica, and small amounts of magnetite, ilmenite, and a carbonate. Much of the mica of the groundmass has lost its original color, and become either green or light brown. Flow structure is very common. The porphyritic phase of the peridotite is confined to the small dikes and to the borders of the large ones.

The non-porphyritic peridotite was originally composed of olivine and biotite, with subordinate amounts of diopside, magnetite, ilmenite, perofskite, picotite, and apatite. Much of the olivine has been changed to serpentine with the formation of magnetite, opal, and a carbonate. The pyroxene is partly altered to calcite and serpentine. The ilmenite and titaniferous magnetite have been partly removed by solution, leaving a white, cloudy substance, leucoxene. The perofskite has partly changed to calcite and rutile. The relations of the minerals indicate that apatite, ilmenite, magnetite, perofskite, and picotite all belong to an early stage of crystallization; following these came the diopside; and still later the mica and olivine. The mica and olivine were in part pyrogenic, as indicated by their mutual interference during growth.

Mineral composition of the rock.—The following tables give approximately the proportions of the different minerals present, as determined by microscopic measurement:

	I	II
Serpentine	55.881	45.927
Biotite	18.285	29.343
Olivine	0.000	10.178
Ilmenite and magnetite	4.257	6.130
Perofskite and picotite	5.563	6.845
Apatite	tr	0.521
Calcite	15.932	0.873
Diopside	0.000	0.000
	99.918	99.817

The section for No. I was taken from near the center of the Glenwood dike, while the one for No. II was taken from near the margin of the same dike. In both cases the rock is considerably altered.

Neither section shows more than one or two crystals of pyroxene, and careful study does not indicate that any large amount was ever present. For purposes of comparison, the calcite and serpentine may be considered as olivine, for it is apparent, from the form of the grains, that they occupy the position of the original olivine grains. The sum of the serpentine calcite and olivine is, for No. I, 71.713 per cent.; for No. II, 56.978 per cent. If these represent the percentages of olivine in the original rock, the evidence of magmatic differentiation is striking. A similar result is obtained by a comparison of the percentages of biotite in the two sections. The comparison of the magnetite and ilmenite is not a safe means of judging, because No. I shows more weathering than No. II, and much of its magnetite has been removed by solution.

The composition of the other dikes shows considerable range, but all may be classified under the head of mica-peridotite—a name proposed by J. S. Diller[1] for a peridotite of similar composition occurring in Crittenden County, Ky.

Contact phenomena.—Along the contact the shaly sandstone and shales are slightly hardened. Near the Cascadilla and Glenwood dikes the rocks are traversed by an unusually large number of joints. There are many irregular cracks in the sedimentary rocks near the contact of most of the dikes. These cracks are filled with calcite. No new minerals occur in the shales, though near the contact they are abundantly impregnated with calcite and are stained with limonite. The contact is irregular, and frequently the lava has extended in long, thin tongues into the bedding planes. This shows the great fluidity of the magma. The same thing is shown in the small dikes at Taghanic where they cut the Genesee shale. There they frequently pinch and swell very rapidly, and often branch from one joint plane to another where two joints intersect. Frequently branches of a dike pass on both sides of a fragment of shale which is thicker than the combined width of the two branches of the dike. The great fluidity of the lava in such cases does not necessarily mean an excessively high temperature, as basic lavas liquefy at comparatively low temperatures. The meager contact effect is explained by thinness of dikes and their low fusion point.

[1] *American Journal of Science*, 3d Ser., Vol. XLIV (1890), pp. 286–89.

The olivine.—Not a single complete grain of olivine was seen in any of the slides, and in several slides it was difficult to find more than a few small fragments of the mineral imbedded in a network of serpentine. The olivine was colorless and contained numerous fine, dust-like inclusions of a dark color, and occasionally grains of a carbonate. Usually the shape of the masses of serpentine indicated that the olivine was in rounded or irregular grains; but occasional sections were found which had sharp crystallographic outlines. Mica scales were found within the serpentine derived from olivine, and some of the grains of serpentine were surrounded by mica. The contact between the two minerals was usually irregular, even when the same grains showed sharp crystallographic outlines elsewhere. This indicates that the two minerals were in part pyrogenic. The olivine enveloped grains of magnetite, perofskite, apatite, and picotite, indicating that these minerals belonged to an earlier stage of crystallization. During the alteration of olivine to serpentine much magnetite was formed. This magnetite occurs in small grains, sometimes so abundant as to make the serpentine appear black. Many of the irregular patches originally occupied by olivine were filled, either wholly or in part, by carbonate. This was doubtless partly dolomite, resulting from the removal of a part of the magnesia and silica, the carbonation of the remaining magnesia, and the infiltration of calcium carbonate. Probably in some cases the magnesia was largely removed, for when the rock was treated with weak HCl it effervesced vigorously for several minutes, indicating the presence of much calcite.

Serpentine.—Serpentine is the most abundant mineral in the rock. It occurs, as pseudomorphs after olivine or pyroxene, in rounded or irregular masses averaging 0.064^{mm} in diameter. It is frequently found inclosing fragments of the unaltered olivine. Two kinds occur: (1) a yellowish fibrous variety, (2) a green fibrous variety. The yellow serpentine has its fibers arranged nearly parallel, and hence its double refraction is considerable. The extinction is parallel. In converging light a biaxial interference figure appears. The axial plane lies at right angles to the fibers, and the black hyperbolas barely remain in the field when a No. 9 objective is used. A faint pleochroism is sometimes noticeable, ranging from green parallel to

the fibers, to brown at right angles to them. The elongation of the fibers is parallel to **c**. Occasionally the yellow serpentine appears granular rather than fibrous. Closely related to the yellow serpentine in optical properties is the nearly clear variety found in the cracks where the original olivine granules were apparently fractured by shearing. The fibers always have the same optical orientation, and stand at right angles to walls of the cracks.

The green serpentine is frequently traversed by fibers, giving a bright interference color. Radiating from these fibers are others which show little double refraction; inclosed by these are light green patches which have low interference colors.

The serpentine contains an abundance of magnetite and a carbonate. The light green patches are almost free from magnetite, except for a small amount of very fine dust. As alteration progresses, the fibers become cleared of magnetite, which is evidently removed by solution, and is taken first from the large cracks where the alteration began. During alteration the amount of serpentine gradually diminishes, and the amount of carbonate increases. In some cases a clear isotropic substance is enveloped by serpentine. This substance, which has a low index of refraction, is probably opal, as the formation of opal and magnetite is a frequent accompaniment of the change of iron-bearing olivine to serpentine. The presence of the carbonate is doubtless due, in part, to infiltration of calcite, in part, to the carbonation of magnesia with the freeing of silica.

Mica.—The mica occurs in light brown crystals averaging 0.04^{mm} in diameter. The mica has a weaker absorption than ordinary biotite, and probably has the composition of phlogopite. Plates cut at right angles to the cleavage frequently show a rim with a reddish-brown color. The same color often shows along the cleavage planes. This colored rim is probably the result of alteration with oxidation of the ferrous iron. As alteration proceeds, this coloring-matter is removed, and the mica becomes lighter colored than it was originally. Frequently three zones of color can be recognized in the same crystal: an inner yellowish-brown zone, surrounded by a zone of reddish-brown color, and this in turn surrounded by a zone which is almost colorless. These zones are optically continuous; but all differ in pleochroism and double refraction. The pleochroism of the light-

brown mica ranges from pale green to yellowish-brown; that of the highly colored border, from green to reddish-brown; and that of the clear margin, from colorless to light brown. The double refraction is high, but as the mica begins to alter, the interference colors appear ragged and are less intense. The extinction angles are usually small. The interference figures range from distinctly uniaxial to biaxial with a very small axial angle. Between the scales of altered mica there are frequently lenticular masses of a carbonate. The mica often alters to chlorite. This alteration was most commonly met with in the porphyritic variety of the rock. In several cases slender needles occur at the contact of an altered mica crystal and serpentine. These needles extend radially from the mica into the serpentine, and are too small to give much indication of their optical properties, except the fact that they are strongly double-refracting, with nearly parallel extinction. They are probably an amphibole.

The mica contained inclusions of magnetite, perofskite, apatite, and picotite, showing that these minerals belonged to an earlier stage of crystallization. There were a few inclusions of serpentine, having a structure which indicated that the original mineral was olivine. Sections in the basal plane showed many fine, dust-like particles of a brown or black color.

There were many large crystals which showed crystal outlines either wholly or in part. The contact between these and the olivine indicated that both were growing at the same time. The mica sometimes extends into irregular embayments in the pyroxene.

Besides the micas described above, there are irregular jagged or shredlike plates of a much smaller size. These surround the alteration products of the olivine, and they may be secondary micas.

Pyroxene.—The pyroxene is a clear, non-pleochroic mineral, containing inclusions of magnetite and perofskite. It is thus seen to belong to a later stage of crystallization than the magnetite and perofskite.

The extinction angles range from 35° to 40°, and the axis of least elasticity which lies in the acute angle β makes an angle of 36–37° with the prismatic cleavage. In converging light the mineral is seen to be biaxial, with a small axial angle. Rectangular cleavage blocks show the emergence of an optic axis. This fact, taken with the rela-

tion of the axis of least elasticity to the prismatic cleavage, indicates that the mineral is the variety of pyroxene called diopside. A trace of a pinacoidal parting shows on sections normal to the prismatic cleavage. The alteration gives rise to a carbonate which often surrounds the crystals and extends along the cleavage cracks. Some of the grains of serpentine with fibers at right angles to each other are doubtless the result of alteration of pyroxene.

Magnetite and ilmenite.—Magnetite is scattered throughout the rock, sometimes in the form of minute grains in the serpentine, and at other times in octahedrons or irregular grains which are as much as 0.03^{mm} in diameter. Cross-sections are quadratic, trigonal, or irregular. The grains in the serpentine are usually very small and result from the alteration of olivine, or, less commonly, pyroxene. As alteration progresses, these fine grains are removed by solution. In the alteration of some of the irregular grains and crystals a white, semi-translucent substance, leucoxene, is produced, indicating the presence of titanium in the form of titaniferous magnetite or ilmenite. Almost all the original crystals appeared to be titaniferous; the only pure magnetite being that resulting from the alteration of olivine and other ferro-magnesian minerals.

Apatite.—Apatite occurs in irregular grains or in slender prisms, which sometimes show a basal parting. It occasionally occurs as inclusions in the olivine or biotite; at other times the grains or crystals are scattered about between the crystals of mica. The apatite is a clear, colorless, non-pleochroic mineral, with a high index of refraction and a low double refraction. Basal sections show a uniaxial interference figure. No alteration takes place, but the surface of the crystals is often pitted.

Perofskite and picotite.—The perofskite occurs in yellowish-brown crystals and grains. The cross-sections are varied, being diamond-shaped, trigonal, hexagonal, or irregular. Many of the irregularities are due to aggregations of crystals. Some skeleton crystals and some incipient forms of growth occur. The index of refraction is high, and the sections are usually entirely isotropic between crossed nicols. The sections are often traversed by irregular cracks, sometimes showing slight alteration. In one case a grain of perofskite which had been included in apatite was partly altered to a carbonate (cal-

cite), containing minute fibers of a clear, non-pleochroic mineral, with high double refraction and nearly parallel extinction. This was probably rutile. Similar alteration was frequently seen elsewhere, and associated with the rutile was leucoxene. Scattered through the sections is a light-yellow mineral, with a slightly lower index of refraction than perofskite. This is probably picotite. It is entirely isotropic between crossed nicols.

Chlorite.—Chlorite is only important along the contact of the dike with the shales, though it also occurs at the contact of mica and serpentine. Doubtless the chlorite is the result of the action of aluminous solutions on the ferro-magnesian mineral olivine.

At right angles to the polarizer the fibers of chlorite are almost colorless, having only a slight yellowish tinge. Parallel to the polarizer the fibers have a bright green color. Basal sections usually have a greenish color. They show a biaxial interference figure with a small axial angle; and the sign is positive. The extinction angles are very small. The fibers are often bent and broken, though few show any crushing of pressure. The variety is probably prochlorite.

Age of the dikes.—The age of the peridotite dikes is a difficult question to solve. That they are younger than the Upper Devonian rocks through which they have been intruded is perfectly evident. During the field investigations certain facts were discovered which may help to fix their age more definitely. The sedimentary rocks have been folded into anticlines and synclines. The age of these folds has been discussed by Mr. E. M. Kindle:

> It appears certain that the comparatively insignificant structural features which have been described are of the same age and origin as the great open folds of the northern Alleghenies. In the quadrangle cornering with the Watkins Glen quadrangle on the southwest are folds whose arches, if restored, would rise 2,500 feet above their troughs. Less than twenty miles to the south of the Watkins Glen quadrangle another great fold shows a crest of similar or greater elevation. From theoretical considerations it would appear improbable that the effects of the epirogenic forces which have developed structures of such magnitude should terminate abruptly at the northern edge of the highly folded belt. Instead of abrupt change from highly folded to monoclinal or nearly horizontal structure, we find the mountain flexures subsiding gradually into the low, gentle swells which have been described. This may be illustrated by a comparison of the maximum dips exhibited by the anticlinal folds encountered between South Mountain in Bradford County, Pennsylvania, and the southern end of Lake Seneca. Eighteen

miles south of the Watkins Glen quadrangle runs the axis of the Towanda anticline between two synclinal mountain ridges—Mount Pisgah and South Mountain. Dips of 70° or more have been observed on the south side of this anticline, but the average dip for the belt of maximum inclination is approximately 40°. The dips of the north limb of this fold are very much lower than the south dips. The writer, although familiar with the region, has not observed any dips which will exceed 20°, and the dips in the zone of maximum inclination will probably not average more than 15°. It is noteworthy that the great excess of the south dip over the north dip of this fold is a characteristic common to nearly all folds of the Watkins Glen quadrangle.[1]

Accompanying the folding were movements along the bedding planes; some minor thrust faults were formed. These two forms of displacement pass into each other. Willis discusses the conditions under which displacements along bedding planes take place, in his article on "The Mechanics of Appalachian Structure:"

> The transmission of pressure through a folding stratified mass may be stated as follows: So long as the stratification is parallel to the original direction of pressure, the force is transmitted as a whole and tends to reduce the volume of the mass; when the strata are inclined to the direction of pressure, the thrust is resolved into two components, the one parallel to the bedding, the other perpendicular to it; the former produces movement when it overcomes the friction on the bedding planes, the viscosity of the strata and any opposing force, as the load; the latter becomes active when it causes some part of resisting mass to move.[2]

It was doubtless the thrust parallel to the bedding planes which produced the displacements under discussion. Where the cohesion between the strata was less than the strength of the rock, the movement took place along the bedding planes; where the cohesion was greater than the strength of the rock, a fracturing of the beds resulted, and movement took place along the fracture plane. Since these disp acements have a bearing on the history of the dikes, a few of them will be discussed here. On the south limb of the Watkins anticline, in Six-Mile Creek, is a small thrust fault which passes into a displacement along the bedding planes. In Shurger's Glen there is a similar fault connected with the anticline which crosses Lake Cayuga near Shurger's Point. In this case the fault passes into displacements along several adjacent bedding planes. On the north

[1] "A Series of Gentle Folds on the Border of the Appalachian System," *Journal of Geology*, Vol. XII, No. 4 (1904), p. 287.

[2] Willis, *Thirteenth Annual Report*, U. S. Geological Survey, Part 2 (1891–92) p. 246.

limb of this same anticline there has been a movement along a bedding plane. This movement has faulted four dikes on the south wall of Taghanic Gorge and three dikes in a gorge east of Ludlowville. The amount of displacement of the ends of the dikes is only about 2 feet, and the movement is largely confined to a single bedding plane. The dikes are nearly at right angles to the axis of the fold, and hence eighteen inches can hardly be taken as the measure of the amount of movement. Probably the movement was nearly parallel to the dikes, and, if so, the amount of actual displacement might be several times the distance between the severed parts of the dikes. Slickensides are not noticeable, but the bedding plane is occupied by a thin layer of pulverized shale. At first the possibility of the dikes having passed for a short distance along this bedding plane was considered. This theory was discarded, because all the dikes showed the same displacement; and the clay between the strata did not contain any of the mica scales which are so prominent in the clays derived from the disintegration of the dikes.

The sequence of the earth movements in this region appears to have been as follows: folding with the development of joint planes; the intrusion of the dikes and their consolidation; renewed folding, accompanied by minor thrust-faulting and movements along bedding planes. The relation of the folds of this region to those of the Appalachian Mountains makes it clear that the periods of folding must have been the same. It follows, then, that the dikes are probably younger than the earliest period of folding and older than the latest. This would fix the date of the intrusion near the close of the Paleozoic.

GLACIATION OF SAN FRANCISCO MOUNTAIN, ARIZONA[1]

WALLACE W. ATWOOD
The University of Chicago

During the summer of 1904 the slopes of San Francisco Mountain were examined with some care, and to the northeast of the main peaks records of ancient glaciation were found. The latitude of San Francisco Mountain is approximately 35° 21′, and the records of glaciation found here may possibly be those of the southernmost ice which existed in this country during the Pleistocene period.

San Francisco Mountain is in the north-central portion of Arizona, about ten miles north of the village of Flagstaff. It is of volcanic origin, having been built by numerous outpourings of lava and by explosions of fragmental material. The ancient crater of this mountain is bordered on the north, west, and south by a series of peaks (see Fig. 1) which are remnants of the once higher rim of the crater. These peaks rise to elevations of from 12,250 feet to 12,794 feet above sea-level, and nearly 7,000 feet above the general level of the plateau on which the mountain stands. To the east the rim of the crater is wanting, and the one stream which drains the central portion of the mountain flows through this opening or gap, and then, turning to the north, descends quickly to the alluvial deposits about the base of the mountain.

The general topographic relations, shown in Fig. 1, indicate that there is today a well-protected catchment area for rain and snow. The high walls on the south and southwest of the basin give the most favorable conditions, in this latitude for the preservation of snows. The floor of the crater varies in elevation from 10,000 to 11,000 feet, and is bordered by the bold, and at places, precipitous, slopes of the lofty peaks which surround it. The dimensions of the catchment basin are best seen in Fig. 1. The total possible area of

[1] The work reported in this article was done in company with a party of students from the University of Chicago, and the author is indebted to the members of the party for assistance in collecting data.

snow accumulation was about one and a half square miles, and the possible depth of snow and ice was somewhere near 2,000 feet.

Ascending the mountain from the east, the first morainic deposits appear at an elevation of about 9,250 feet and at a distance of about two miles from the head of the basin. At this point morainic ridges

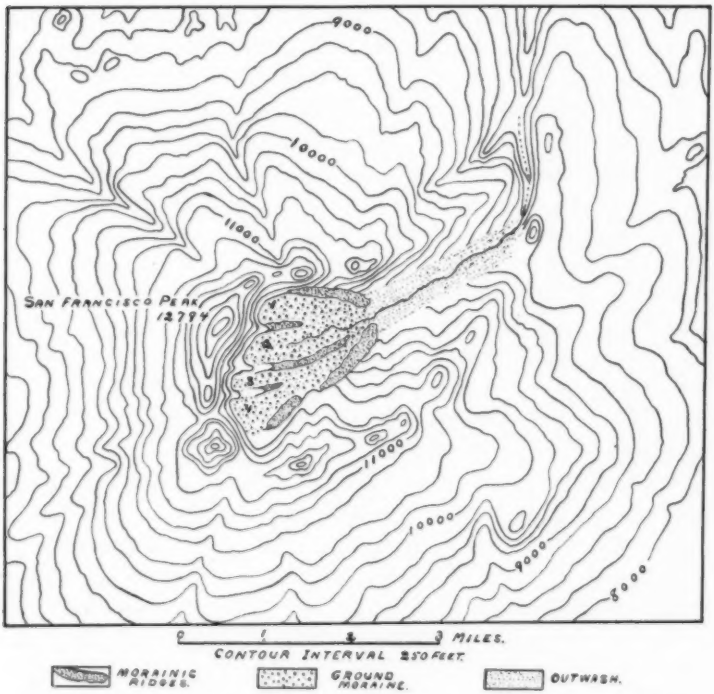

FIG. 1.—Topographic sketch of top of San Francisco Mountain, Arizona.

jut out into the valley from either side, but fail to cross the stream course and unite. This connection was probably complete at one time, but the material of the terminal moraine has been largely washed away.

Down-stream from the position of the terminal moraine there is a heavy alluvial deposit, made by torrential waters issuing from the end of the glacier. This outwash or valley train extends at least one

and a half miles down-stream, and perhaps much farther, but farther out it would be difficult to distinguish it from the preglacial and post-glacial alluvial deposits.

Up-stream from the position of the terminal moraine, the drift ridges, already mentioned, swing to appropriate positions for lateral moraines and continue to the lower margin of the basin, as shown in Fig. 1. The crests of these moraines are commonly but 40–50 feet above the valley bottom, but they increase in elevation to the eastward, until at their down-stream termini they are at least 100 feet high. The valley between the lateral moraines contains a drift-filling which at places is more than 50 feet deep, and which may perhaps be classed as ground moraine. In addition to the lateral and ground moraines, there are medial moraines projecting down-stream from the rock spurs which subdivide the basin.

The topography and topographic relations of these deposits of loose material are such that it would be extremely difficult, if indeed possible, to account for their formation under any other hypothesis than that of glaciation, but an examination of the material in these deposits furnishes conclusive corroborative evidence of glaciation. The material is entirely volcanic, but nevertheless has the characteristic physical and lithological heterogeneity of glacial drift. Bowlders up to 10 feet in diameter are found in the moraines, and in the exposed sections there is every gradation down to the very fine material in which the stones are imbedded. In all the exposures seen the drift was unstratified. Many of the larger stones and bowlders are sub-angular in form, with smooth and polished surfaces. In a region of undoubted glaciation, such forms and surfaces would have been accepted as positive evidence of ice-action, but in this region more conclusive evidence was looked for, and in the fresher exposures, especially in the débris from a 30-foot excavation in the bottom of the valley, beautifully striated stones were found.

The basin is not cirque-like in form, and probably it was not greatly modified by the ice. It is subdivided at its head by projecting rock spurs into four minor upper basins (1, 2, 3, 4, Fig. 1). Basins 1 and 2 have floors which are broader than would be expected if developed by stream-erosion alone. On the floor of the basin numbered 1, a surface of bed-rock is exposed which has been polished and

grooved. The stoss sides of all minor prominences on this rock are characteristically worn. On the floor of the basin numbered 2, there are irregular hillocks or mounds which were formed by the ice, and among them were formerly small ponds or marshes. The minor basins numbered 3 and 4 show little modification due to ice, but it may be that the extensive talus slopes obscure the former flat bottoms of these basins. No proof of more than one epoch of glaciation was found.

Since the melting of the ice, the amount of erosion accomplished has not been great. Much of the talus material about the rim of the crater is presumably of postglacial age, but the washing away of the terminal moraine along the main stream is the most conspicuous task that has been done. The surface-weathering of the glacial material is so slight as to be insignificant.

In comparison with the records of ice-action in higher latitudes in this country, the records on San Francisco Mountain are meager. They indicate appropriately weaker glaciation in this lower latitude.

A CORRECTION

CHARLES R. VAN HISE
University of Wisconsin

In Monograph 47 of the United States Geological Survey, *A Treatise on Metamorphism*, a serious mistake is made in reference to the redistribution of sodium. It is stated on p. 997 that the deficiency of soda in the sediments as compared with the original rocks is 2.4985 per cent., and that this deficiency amounts to 70.38 per cent. of the whole. In estimating the deficiency in metric tons for the soda, the computor, instead of using the amount of soda in the original rocks as the base, took the weight of the entire mass of sediments, and thus the deficiency of soda is given as 475,065,000,000,000,000 metric tons, whereas it should be 16,864,875,000,000,000 metric tons. The total amount of soda in the ocean, 19,101,000,000,000,000 metric tons, instead of being but a small fraction of the total deficiency for the sediments, is 13.2 per cent. in excess of the deficiency.

This error requires the modification of a number of statements made on p. 998. It is there stated that the result obtained suggests that the soda of the salt deposits of the land is probably greater in amount than in the salt of the sea, whereas the true result indicates that the soda of the salt deposits of the land is unimportant as compared with that in the sea. Also a criticism in reference to calculating the age of the earth from the amount of salt in the sea is without force.

No adequate excuse for the error in calculation can be offered; it can only be said that it occurred. In the *Treatise on Metamorphism* there are the results of thousands of numerical calculations. In the one cited a blunder was overlooked. We hope that for the most part the calculations will be found substantially correct.

Reviews

Report on the Origin, Geological Relations and Composition of the Nickel and Copper Deposits of the Sudbury Mining District, Ontario, Canada. By A. E. BARLOW. (Annual Report of the Canadian Geological Survey, Vol. XIV. Part H, 1904.) With geological maps.

Dr. Barlow publishes in this report the results of his careful and exhaustive study on the Sudbury nickel district of Ontario. He makes the succession as follows:

1. *Lower Huronian.*—No rocks of this age are at present known in the nickel-bearing area, but this period is represented, in part, by the banded siliceous magnetites and associated rocks of the townships of Hutton and Wissner.

2. *Upper Huronian.*—(A) Diorites, hornblende-porphyrites, and green schists; (B) conglomerates, graywackes, and quartzites; (C) norite and diorite (Worthington mine belt, and areas southeast of Evans mine and east of Sudbury).

3. *Laurentian.*—Granite and diorite-gneiss near Wahnapitae station.

4. *Upper Huronian* (?).—Tuffs, felspathic sandstones, and slates classified provisionally on previous geological maps as of Cambrian age.

5. *Post-Huronian.*—(A) Granites; (B) nickel-bearing eruptive of the main belt (quartz-hypersthene-gabbro or norite, diorite, with their peculiar differentiation product, micropegmatite). (C) dykes of olivine diabase.

On the accompanying maps the rocks are separated lithologically and are all bracketed under the general heading "Archean." All of these terms are used in the sense commonly given them by the Canadian Geological Survey. The district is closely related with the Lake Superior region on the west, and there the U. S. Geological Survey uses different terms for what are believed to be equivalent series. Barlow's Lower Huronian may be correlated with the Archean of the U. S. Geological Survey; Upper Huronian, with the U. S. Geological Survey Lower Huronian; Laurentian, with the granites mapped as intrusive into the Huronian of the U. S. Geological Survey; Upper Huronian (?) with the Upper Huronian of the U. S. Geological Survey.

The nickel and copper are confined to the norite and its altered varieties. Closely associated with this is a rock of granitic composition of prevailing gneissoid texture, which cannot be sharply separated from the basic eruptive, although the change is usually sharp enough to allow of a boundary being drawn between them. The norite ranges, as shown by Coleman, are probably the exposed portions of one continuous laccolite, with occasional minor irregularities or offsets, which has been folded into a platter-shaped trough, holding in its depressed interior nearly flat-lying Huronian (?) sediments constituting the uppermost series of the district. The relations of these sedimentary rocks to the norite are in doubt, but later work seems to indicate a close relationship, both in origin and age, with the main masses of norite.

The nickel is mainly in the form as a nickel iron sulphite, pentlandite, associated with pyrrhotite and chalcopyrite. That the ore has been segregated more or less directly from magma is believed to be shown by the following facts:

The deposits, without exception, all occur at the margin of the gabbro or norite, the rock itself in immediate association with the ore being finer in texture, and relatively much more basic in composition, than portions further removed from the contact.

The sulphides are always much more sharply defined against the walls of the intrusion than on the inner side towards the main mass of the gabbro.

These deposits are always found in such intimate association with the norite or hypersthene gabbro.

Pyrrhotite, chalcopyrite, and pyrites are all ordinary constituent minerals of the normal norite, and are, at times, comparatively abundant even in exposures situated some distance from the contact.

The sulphides are, undoubtedly, of primary origin, and are among the earliest of the minerals to crystallize out from the original magma, sometimes even antedating the iron ore, in which they are occasionally completely inclosed.

The transitional type between the normal norite and the richer forms of the pyrrhotite-norite furnishes unmistakable evidence that in these cases, at least, the sulphides were formed during the cooling and crystallization of the norite magma, and that they were very little affected by any secondary action.

Secondary quartz, calcite, and dolomite are occasionally present, in appreciable amounts, but the prevailing scarcity of these minerals at most of the deposits has always been a subject of remark.

The deposits are singularly uniform in chemical and mineralogical

composition, and their monotonous character, in this respect, has been frequently commented upon.

Brecciation, which is so frequently characteristic of these deposits, is an almost constant feature of eruptive contacts, resulting from the detaching of material from the containing walls.

This conclusion is in accord also with evidence drawn from analogy with chemical and metallurgical principles.

Dr. Barlow concludes further that there can be little doubt of the abundant presence of heated solutions and vapors, which were capable of dissolving out, and, under certain conditions, redepositing these sulphides. Such agencies certainly began their work before the whole magma had cooled, bearing their heavy burdens of sulphide material, most of which was obtained from the magma in the immediate vicinity,to occupy the various cavities and fissures as fast as these were formed. The whole of this action was practically completed before the intrusion of the later dikes of the olivine-diabase, which are now regarded by Dr. Barlow as the end product of the vulcanism to which the norite masses owe their intrusion. In certain of the deposits the various hydrochemical agencies accompanying dynamic action have been more active than in others, as at the Victoria mine, and some of the Copper Cliff mines, but in others—as, for instance, the Creighton mine—magmatic differentiation has been the main and almost sole principle determining and favoring the development of this, the largest and richest sulphide nickel mine in the world.

The evidence summarized by Dr. Barlow seems to show beyond reasonable doubt that the norite is the original source of these sulphides. However, he describes evidence of redistribution by aqueous and gaseous solutions accompanying later stages of the norite eruption, and it is difficult to see how this evidence will enable one to draw any line between, or determine relative emphasis to be placed on, redistribution by such agencies and redistribution by meteoric waters heated by contact with the cooling norite or by meteoric waters acting subsequent to its cooling. Difference in emphasis on these factors now constitutes the main outstanding difference of opinion as to the origin of the ores.

The report is accompanied by a brief description of the geology of well-known nickel deposits of the world, and a summary of the metallurgical principles applicable to the extraction of nickel, making it useful as a nickel handbook. All interested in the geology of ore deposits will appreciate Dr. Barlow's adequate and satisfactory treatment of his subject.

Reference should be made to two other reports on the district which have appeared in the last two years—one by Mr. Charles W. Dickson, in

Vol. XXXIII of the *Transactions of the American Institute*, 1903, and another by Professor A. P. Coleman, in the *Annual Report of the Bureau of Mines of Ontario*, 1903. Dr. Barlow is in essential accord with Professor Coleman, though differing in details and emphasis on certain points. He differs from Mr. Dickson in putting emphasis on the magmatic segregation of the ore rather than on the secondary concentration. Dickson concludes that the preliminary concentration accompanying the intrusion of the norite was comparatively slight; that appeal must be made to a more distant source of the metals, probably minutely disseminated in the rocks through which the depositing solutions passed; and that, in general, the whole weight of the evidence points to the secondary formation of the Sudbury ore-bodies as replacements along crushed and faulted zones, with only minor indications of open cavities.

C. K. L.